Studying Short-Range Nucleon-Nucleon Interactions with an EIC

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EIC Task Force Meeting

<u>Reference:</u> Phys. Rev. **C93** (2016) 045202 [arXiv: 1512.03111]

Outline

I. Motivation

II. The Proposal

III. Proof of Principle

IV. Feasibility

V. Conclusions

1. Motivation:

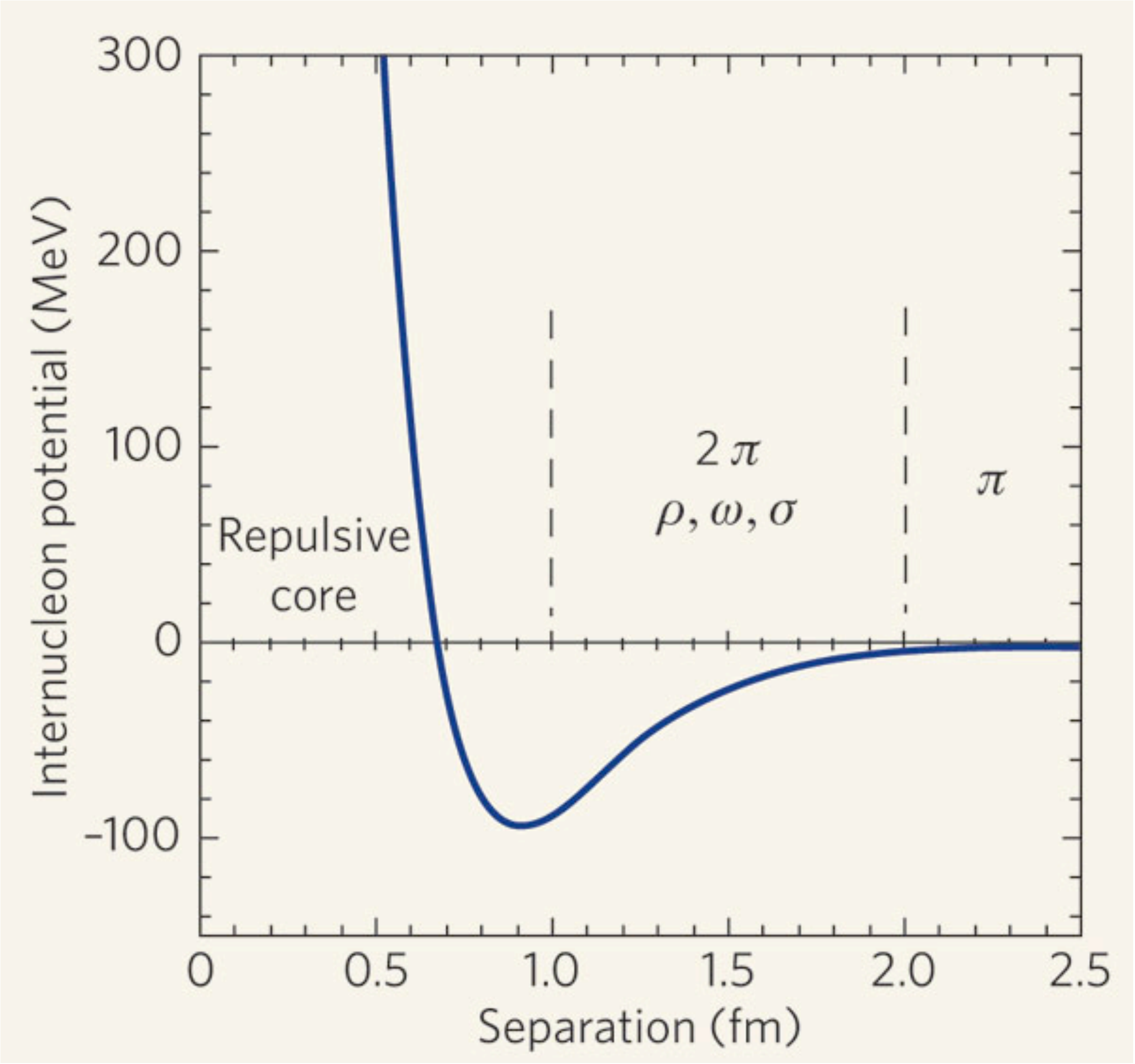
Looking for QCD in the NN Potential

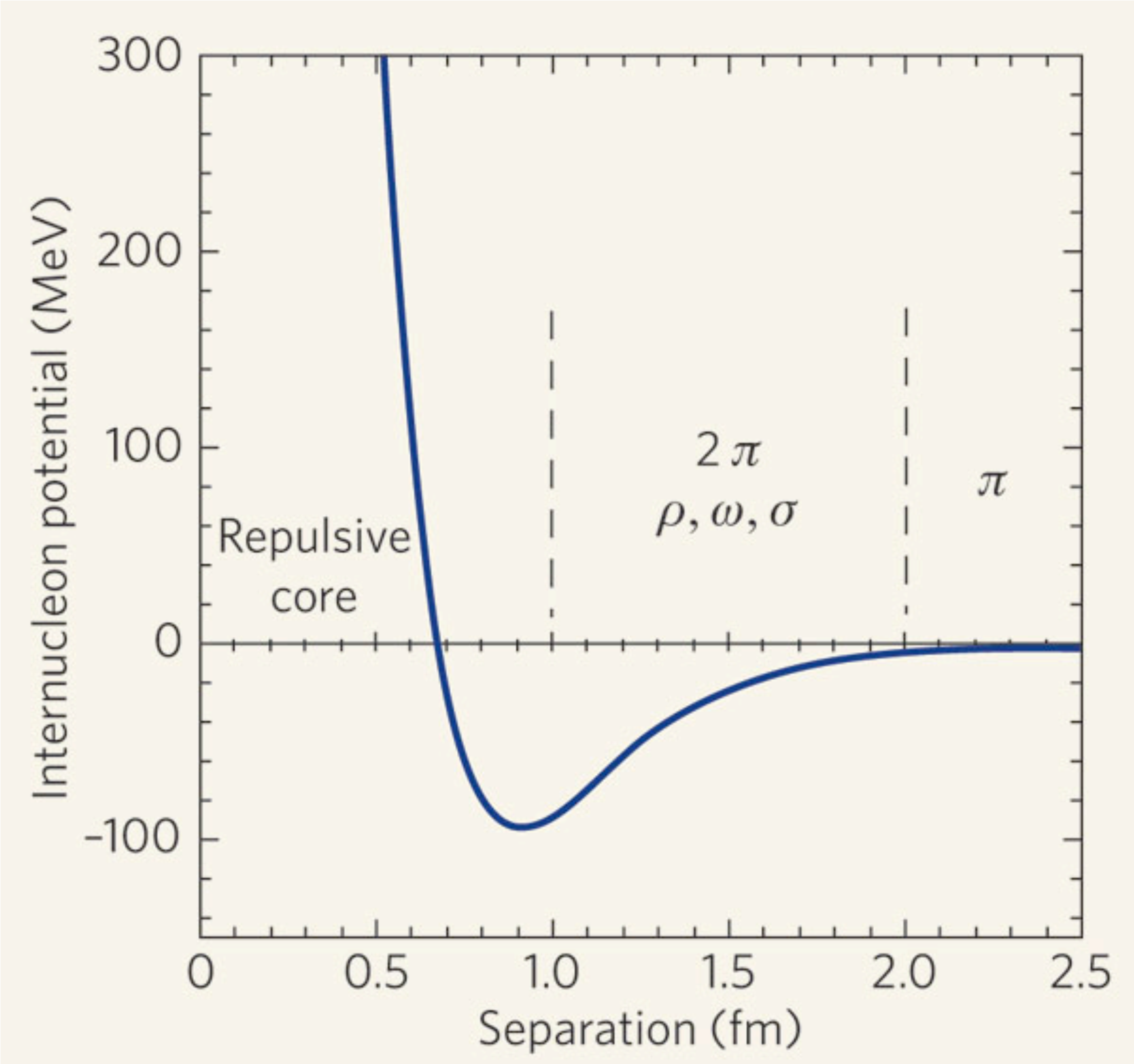
Emergence of the NN Potential from QCD

- The inter-nucleon potential is an emergent, non-perturbative consequence of QCD.

- Described using effective field theories as an exchange of various effective bosons.

➡ The exchanged particles (and their properties) vary for different distance scales...



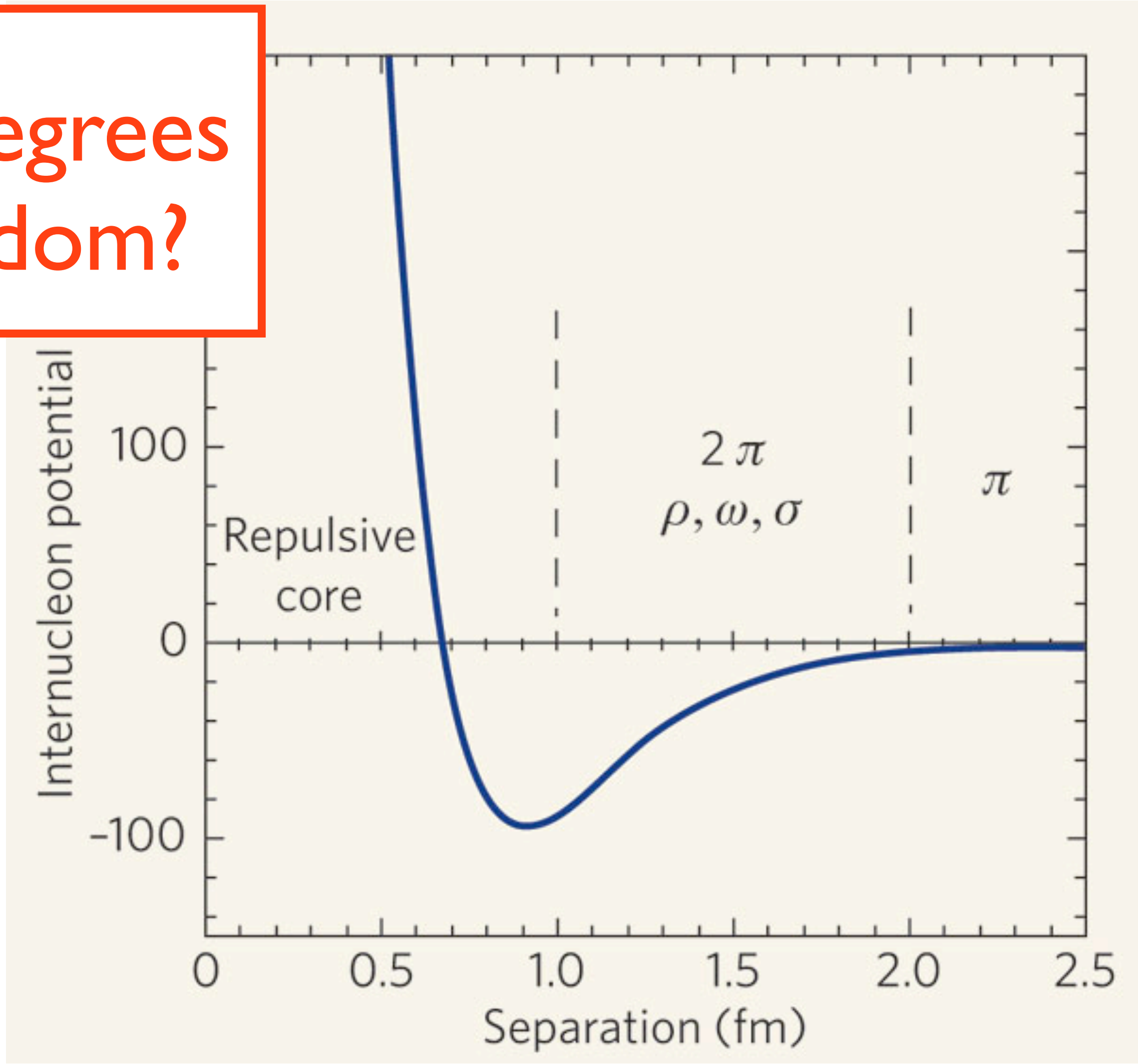


M. Sargsian 1403.0678

$r \geq 2\ fm$	Yukawa pion exchange
$2\ fm \geq r \geq 1.2\ fm$	2-pion exchange, etc. ; tensor force
$1.2\ fm \geq r \geq 0.7\ fm$	Vector boson exchange
$0.7\ fm \geq r$	Repulsive core ; highly virtual bosons...

Breakdown of Effective Theories at Short Distances

QCD degrees of freedom?



"In fact a 'pion far off its mass shell' may be a meaningless - or at least highly complicated idea."

\- R. Feynman

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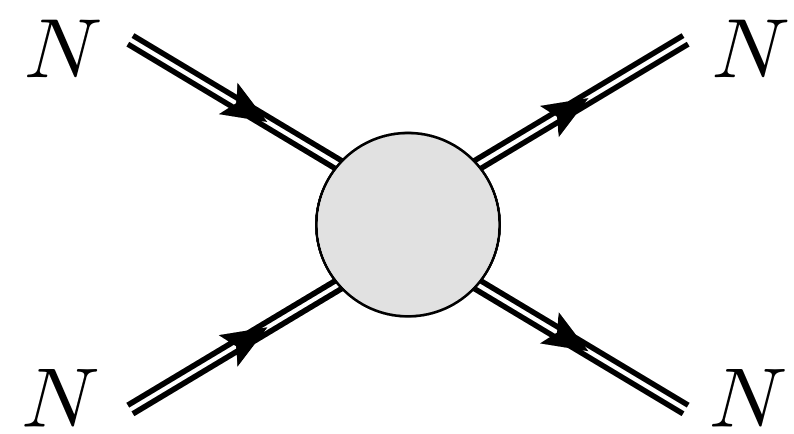
The Direct Approach: Elastic NN Scattering



- The most direct way to access the short-distance NN potential is through elastic scattering.
  - ➡ For fixed-angle scattering, there is only one dimensionful scale:

$$Q^2 \equiv -t = \frac{1}{2} s \left(1 - \cos\theta_{cm}\right)$$

  - ➡ Hard scattering $Q^2 \gg \Lambda_{QCD}^2$ is mediated by QCD degrees of freedom.

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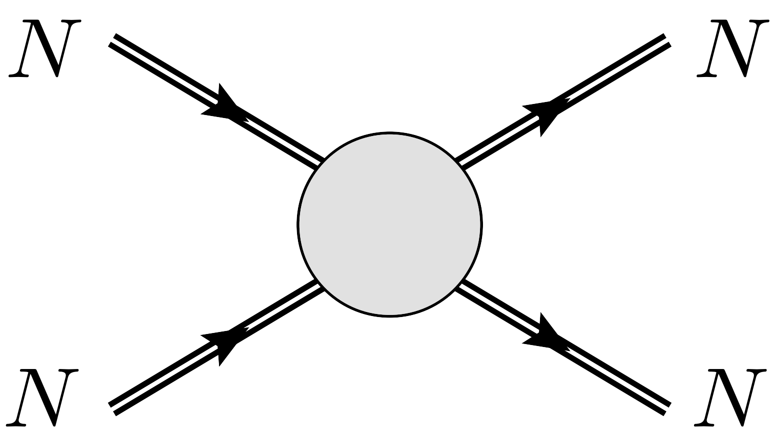

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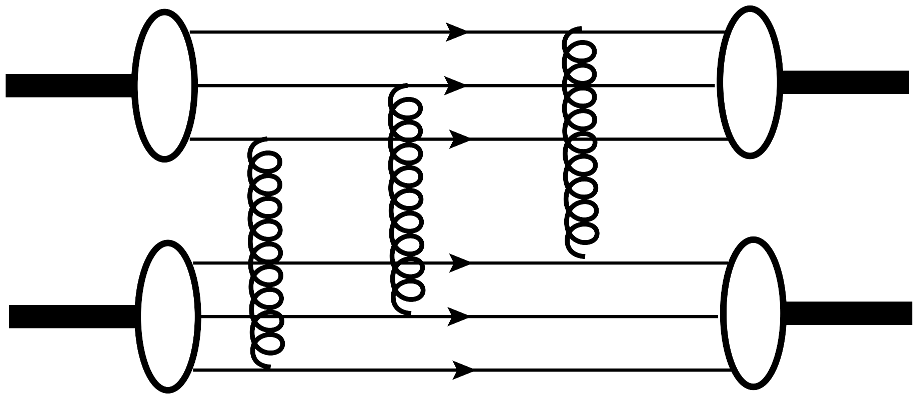
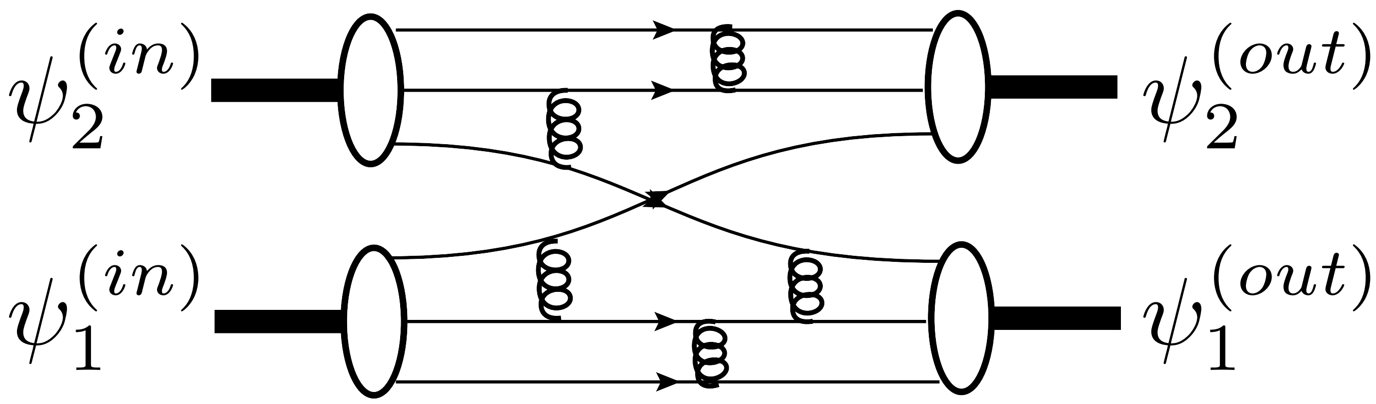
  - ➡ Hard scattering $Q^2 \gg \Lambda^2_{QCD}$ is mediated by QCD degrees of freedom.

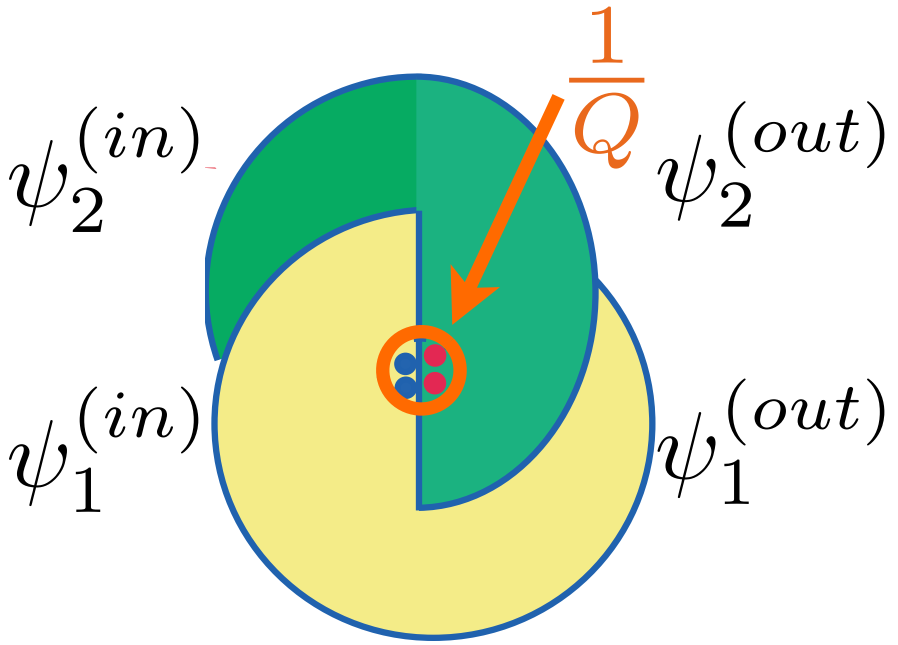
- For the nucleons to remain intact, their partons must be (nearly) collinear
  - ➡ Need multiple hard momentum kicks to (at minimum) all 3 valence quarks



One Hard Reaction: Quark Counting Rules

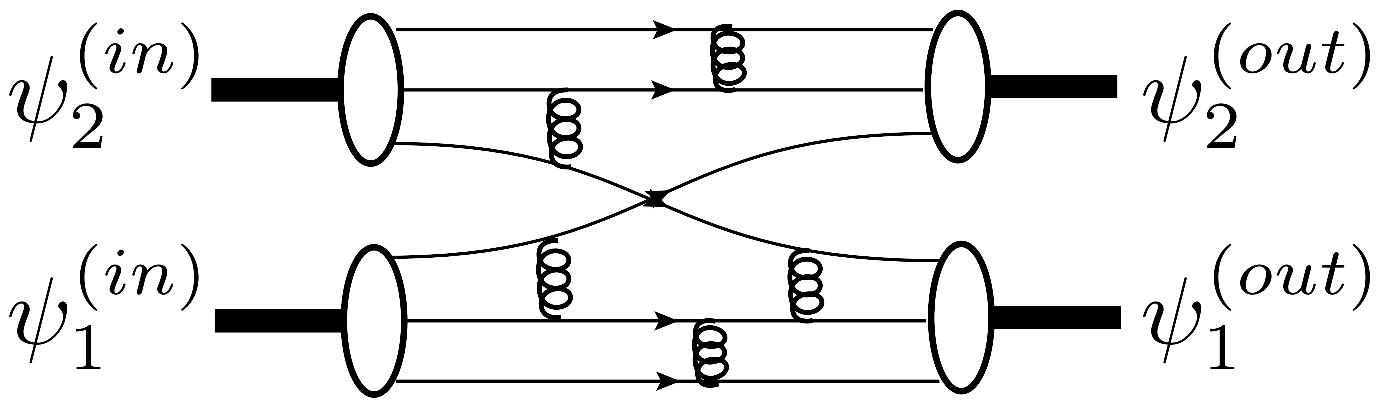
G. Sterman 1008.4122

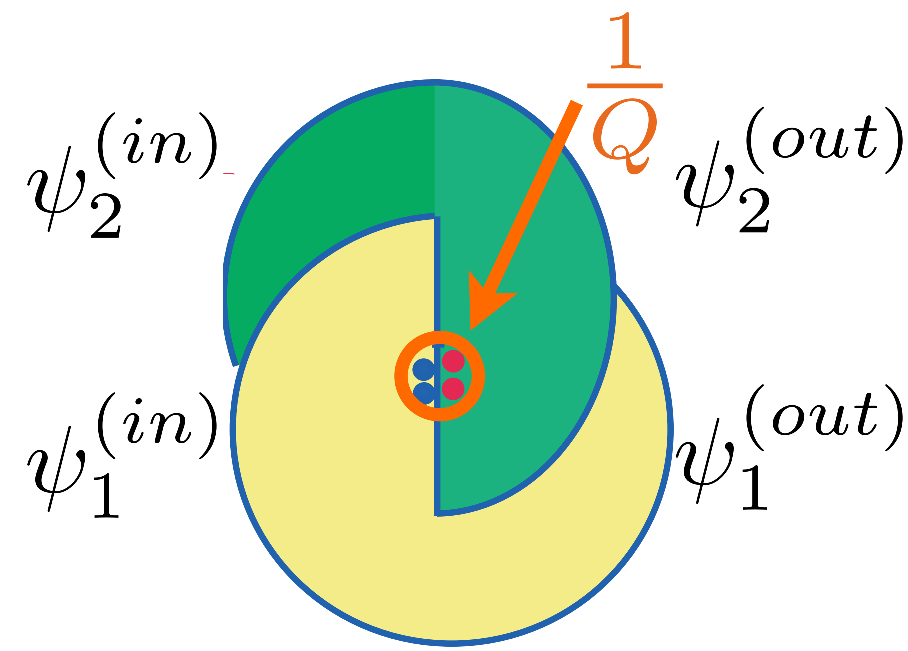




- One hard reaction with all 3 valence quarks close: $\Delta x \leq \frac{1}{Q}$

G. Sterman   1008.4122





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$$\frac{d\sigma}{dt} \sim \int d^2x \, |\psi_1^{(in)}(x,x,x)|^2 |\psi_2^{(in)}(x,x,x)|^2 |\psi_1^{(out)}(x,x,x)|^2 |\psi_2^{(out)}(x,x,x)|^2$$

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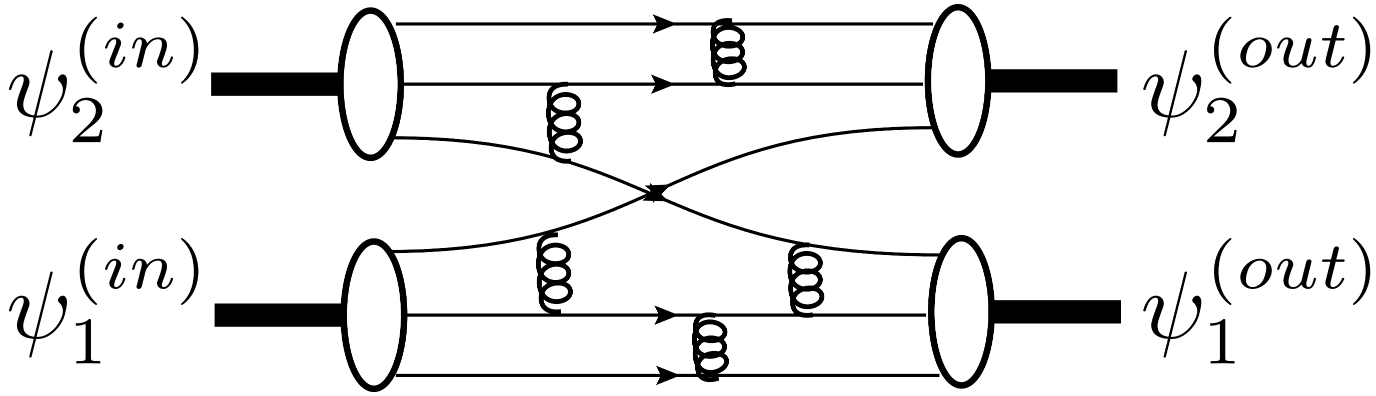

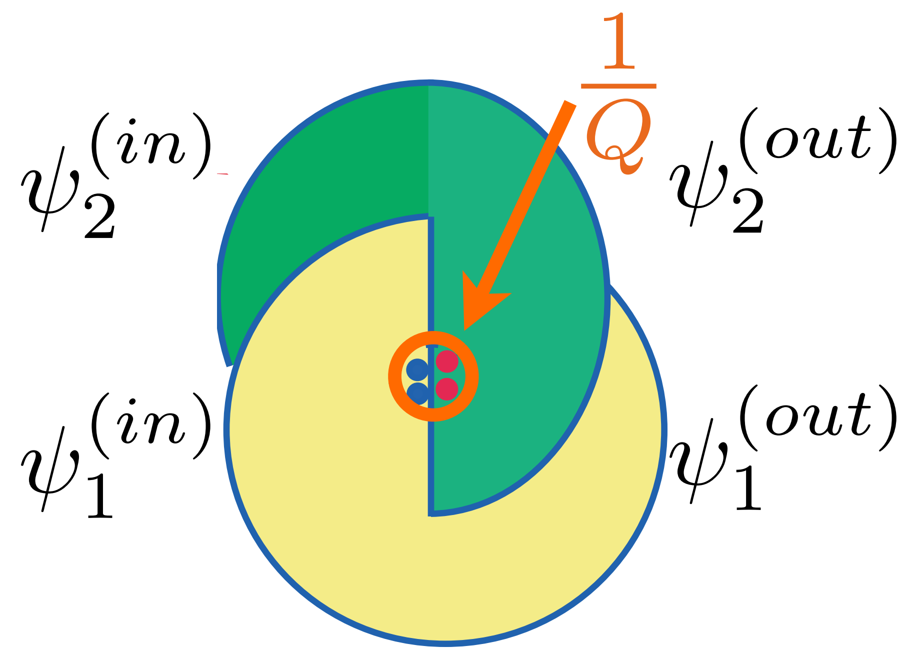

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$$\frac{d\sigma}{dt} \sim \frac{1}{s^2}\left(\frac{m^2}{Q^2}\right)^8 \sim \boxed{\frac{1}{s^{10}}}$$

Brodsky-Farrar quark counting rules

Independent Hard Reactions: Landshoff Mechanism

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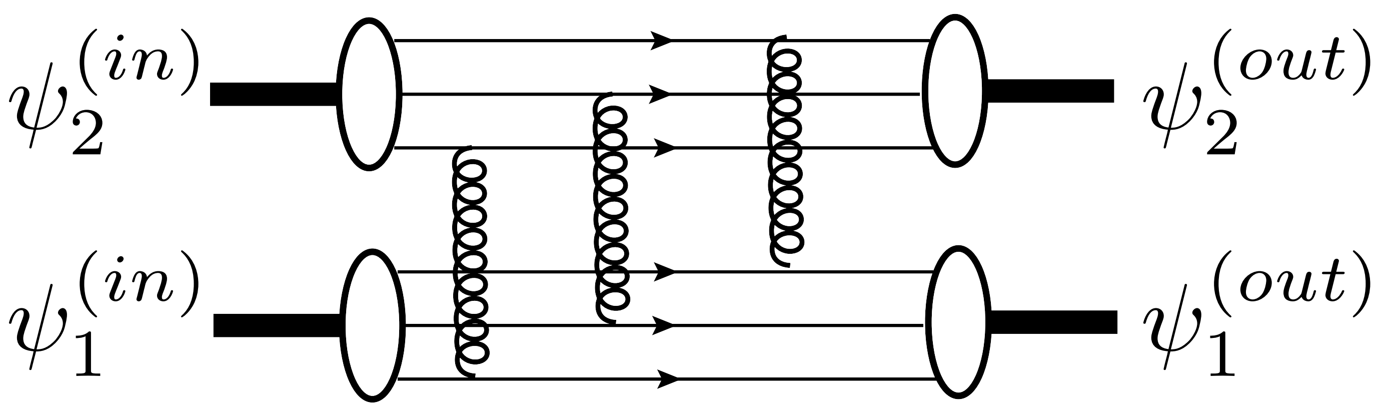

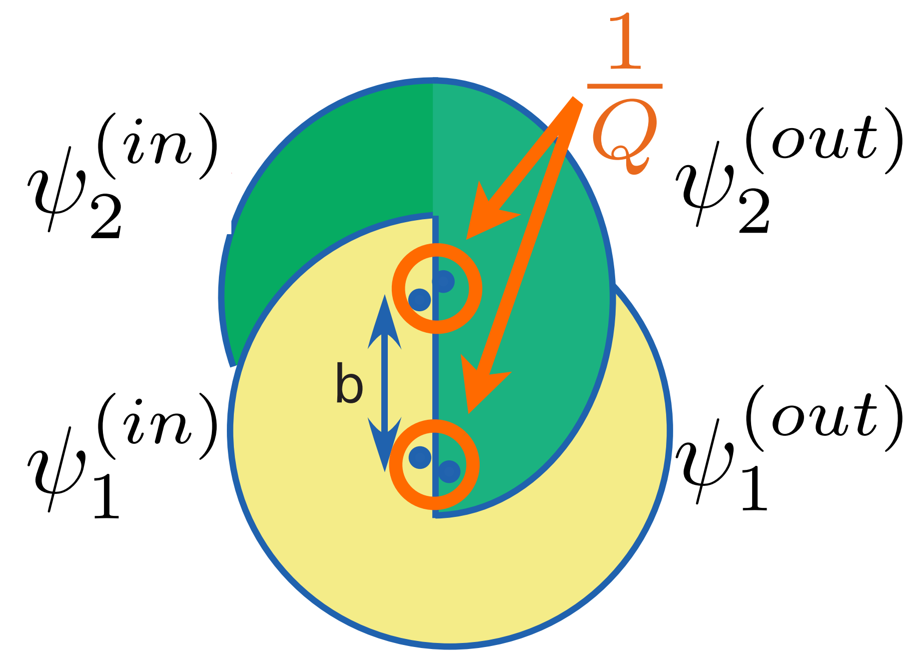

- Separate independent hard reactions lead to a "geometric enhancement" of the cross-section.

Independent Hard Reactions: Landshoff Mechanism

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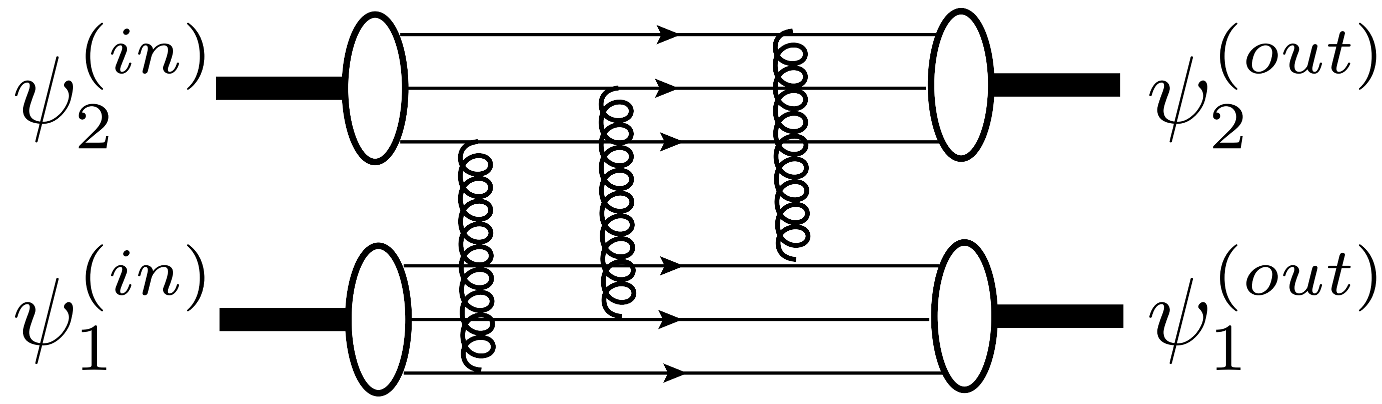

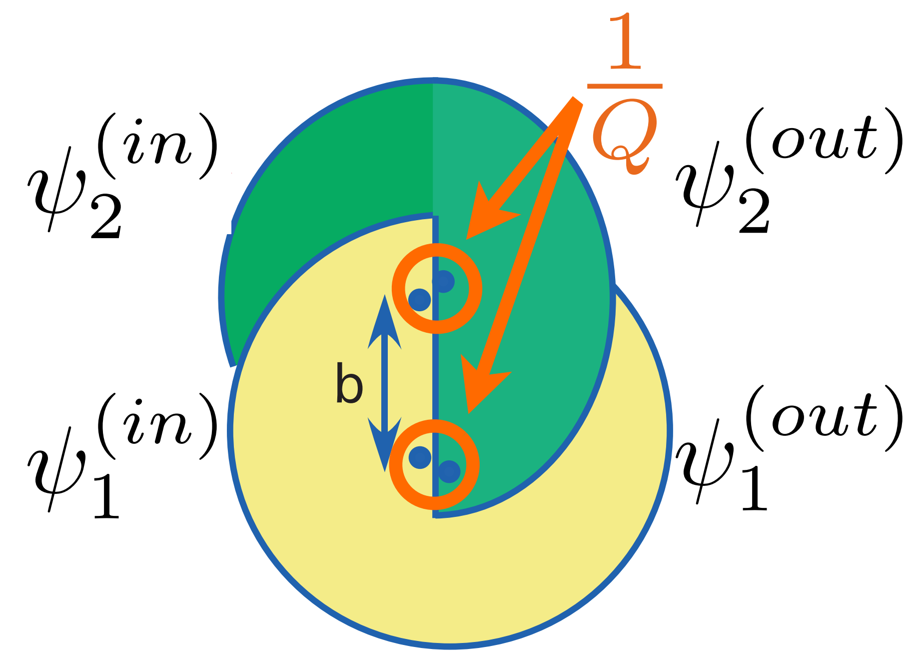

- Separate independent hard reactions lead to a "geometric enhancement" of the cross-section.

$$\frac{d\sigma}{dt} \sim \int d^2x\, d^2y\, d^2z\, |\psi_1^{(in)}(x,y,z)|^2 |\psi_2^{(in)}(x,y,z)|^2 \times |\psi_1^{(out)}(x,y,z)|^2 |\psi_2^{(out)}(x,y,z)|^2$$

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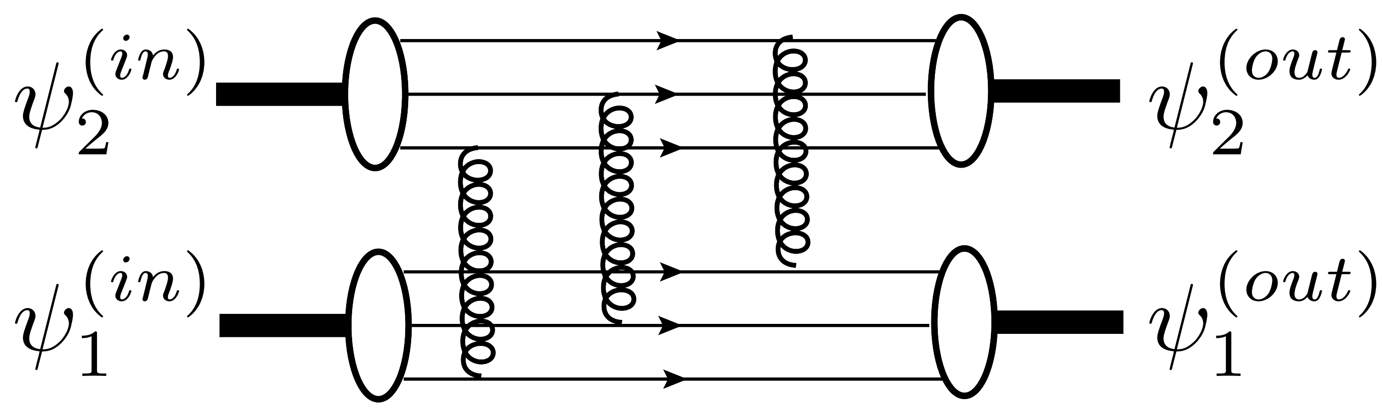

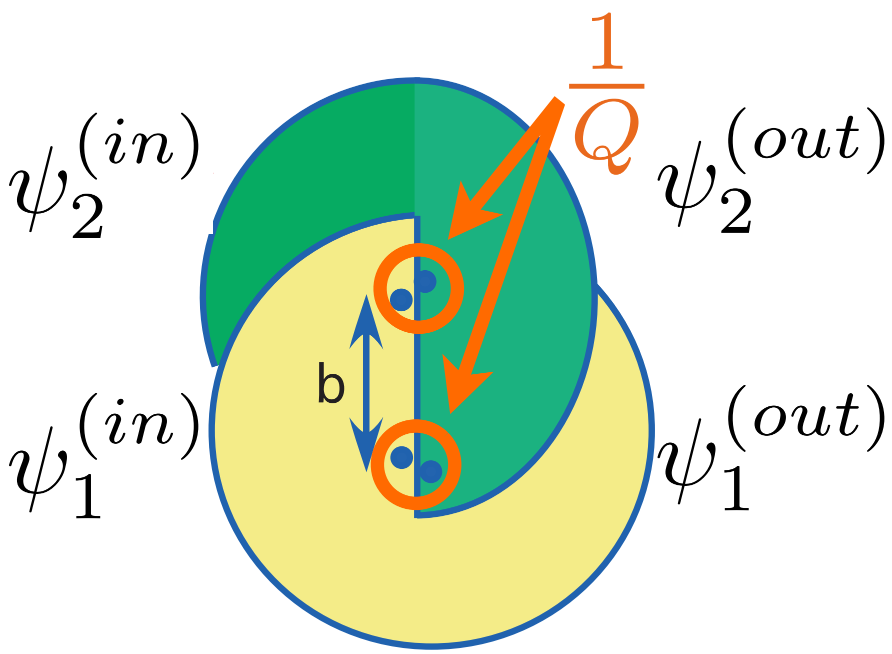

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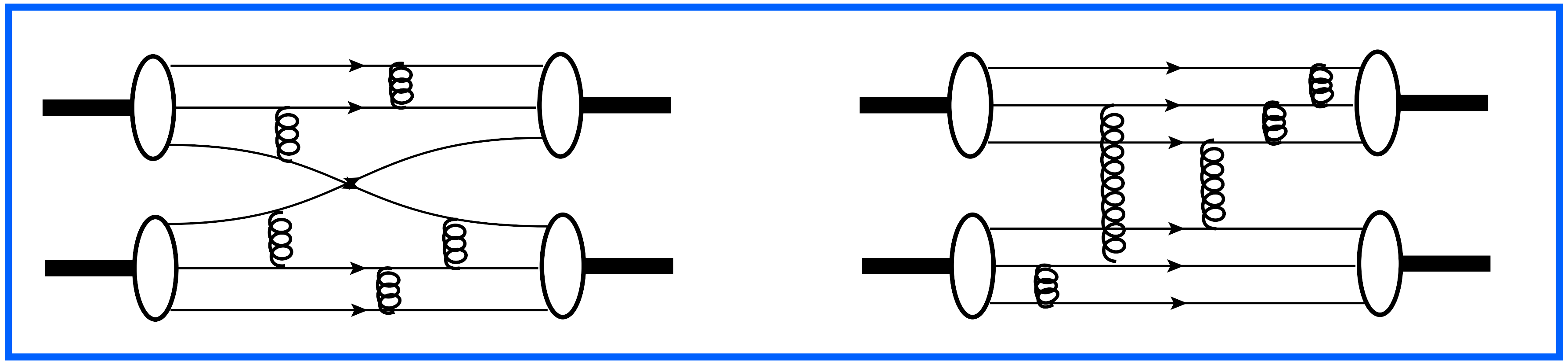
$$\frac{d\sigma}{dt} \sim \frac{1}{s^2}\left(\frac{m^2}{Q^2}\right)^6 \sim \boxed{\frac{1}{s^8}}$$ Landshoff mechanism

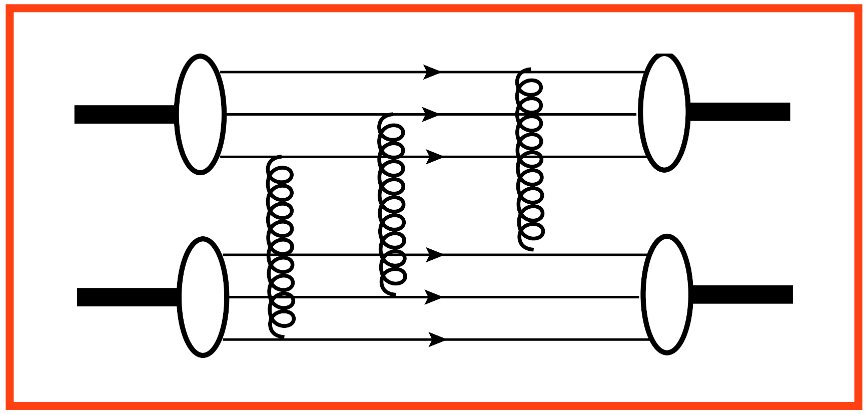
pQCD Favors Gluon Exchange...

M. Sargsian 1403.0678

Brodsky-Farrar: s^{-10}



Landshoff: s^{-8}

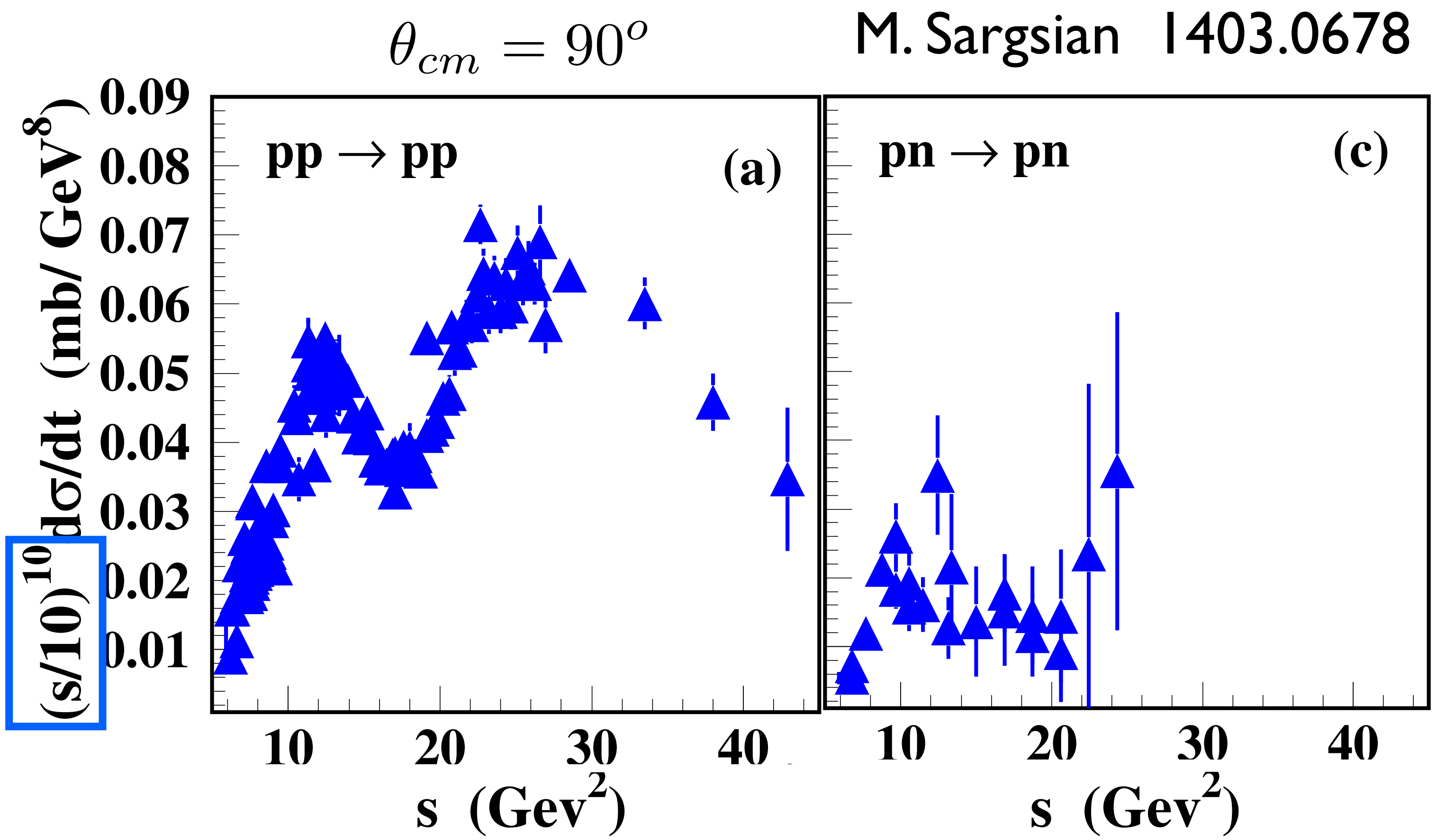


- Expect Landshoff gluon exchange mechanism to dominate:

➡ Elastic NN scattering should scale as s^{-8}

➡ Gluon-mediated scattering is flavor-independent:

$$\begin{cases} pp \to pp \\ pn \to pn \\ p\bar{p} \to p\bar{p} \\ \vdots \end{cases}$$



- Scales like Brodsky-Farrar: s^{-10}

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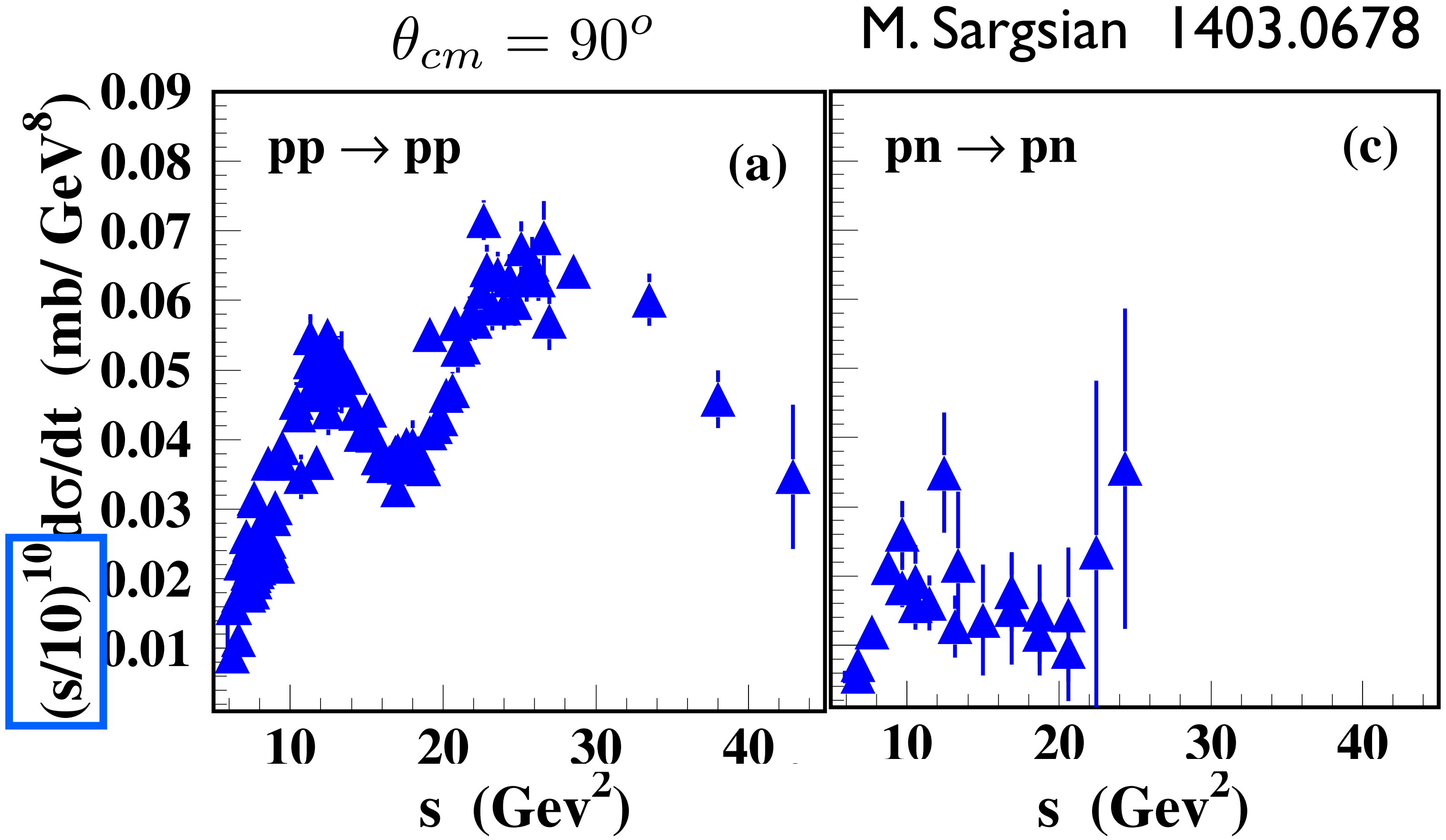
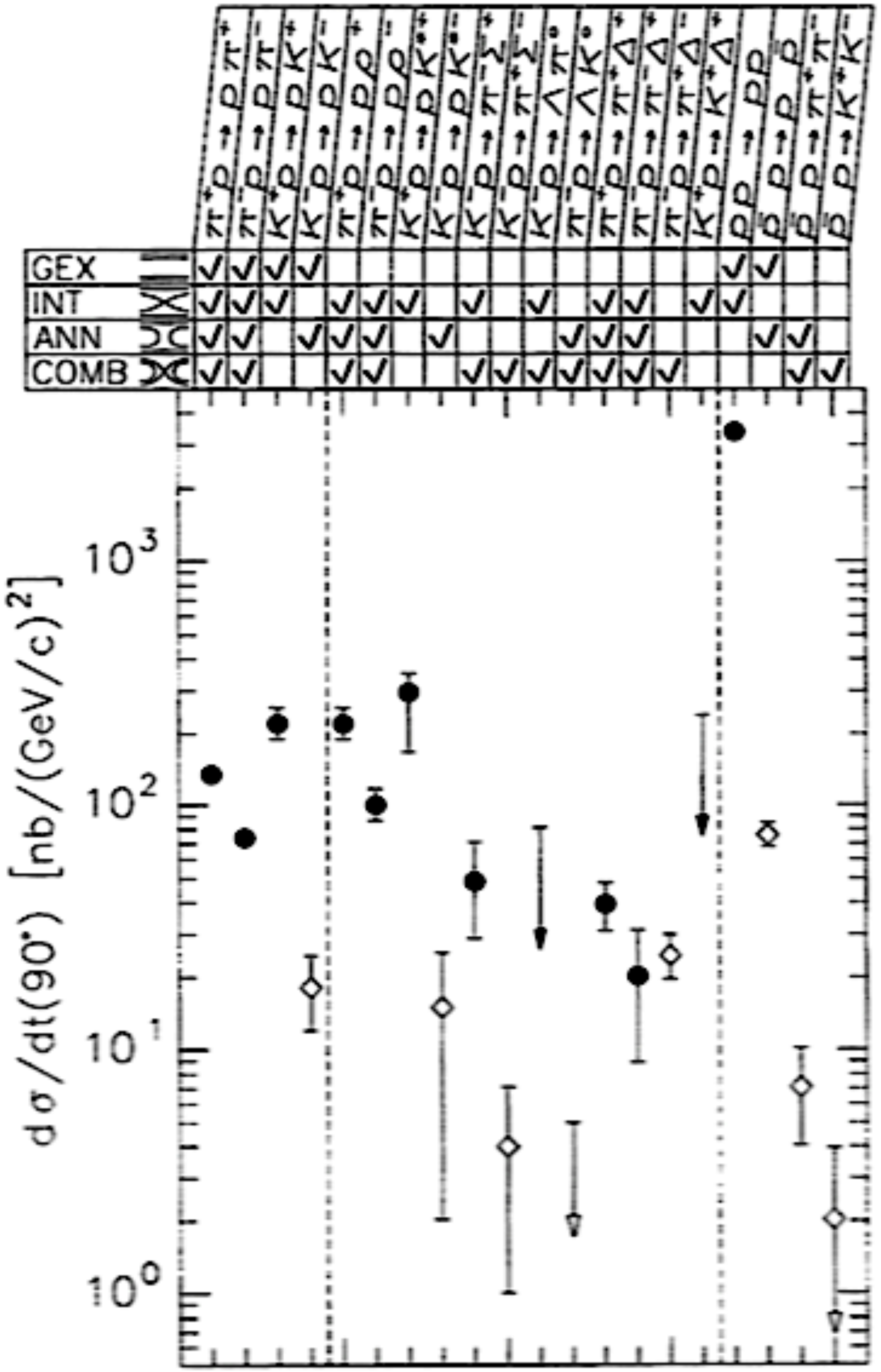
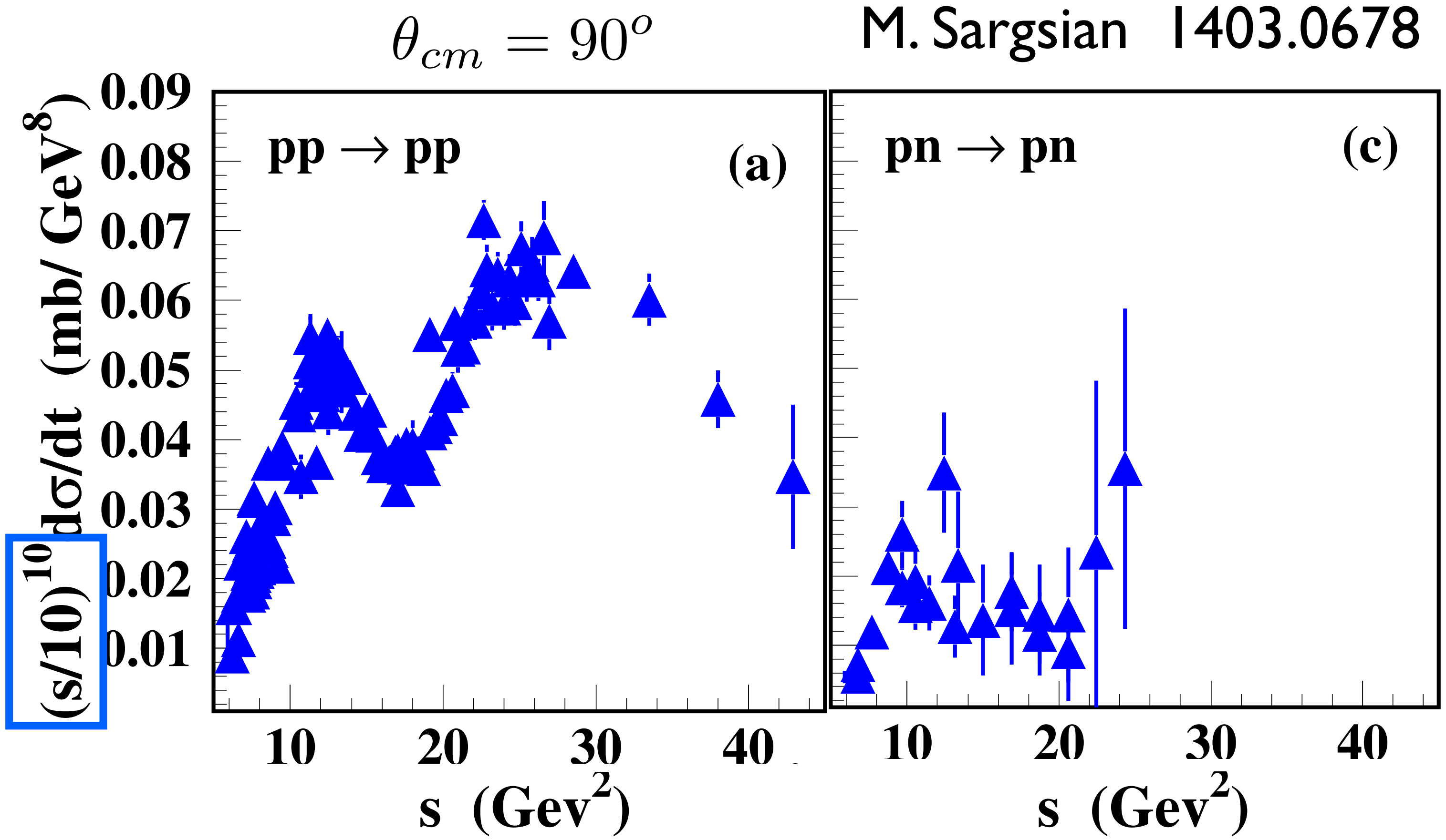


- Scales like Brodsky-Farrar: s^{-10}
- Flavor dependence favors quark interchange



White et al., PRD**49** (1994)



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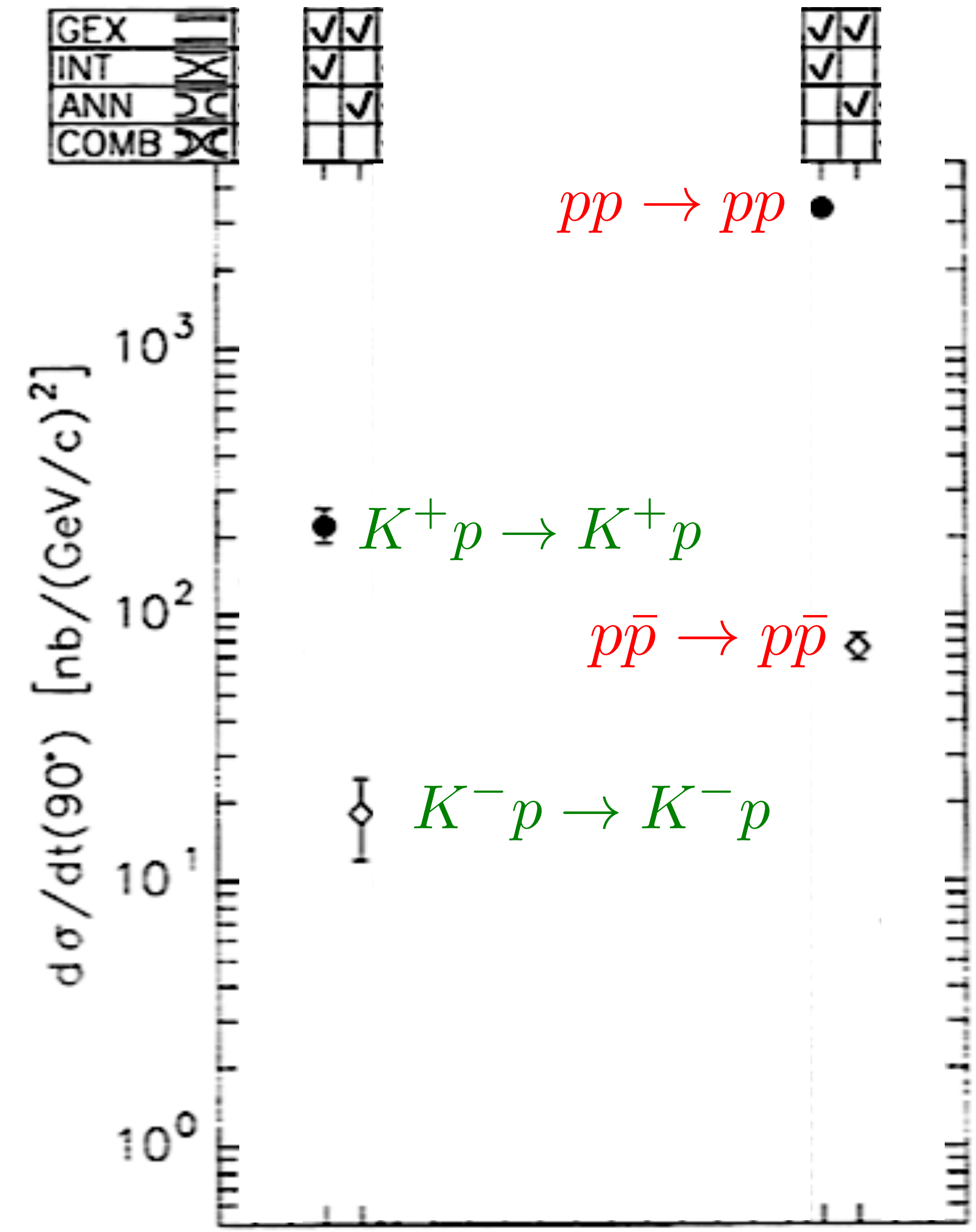
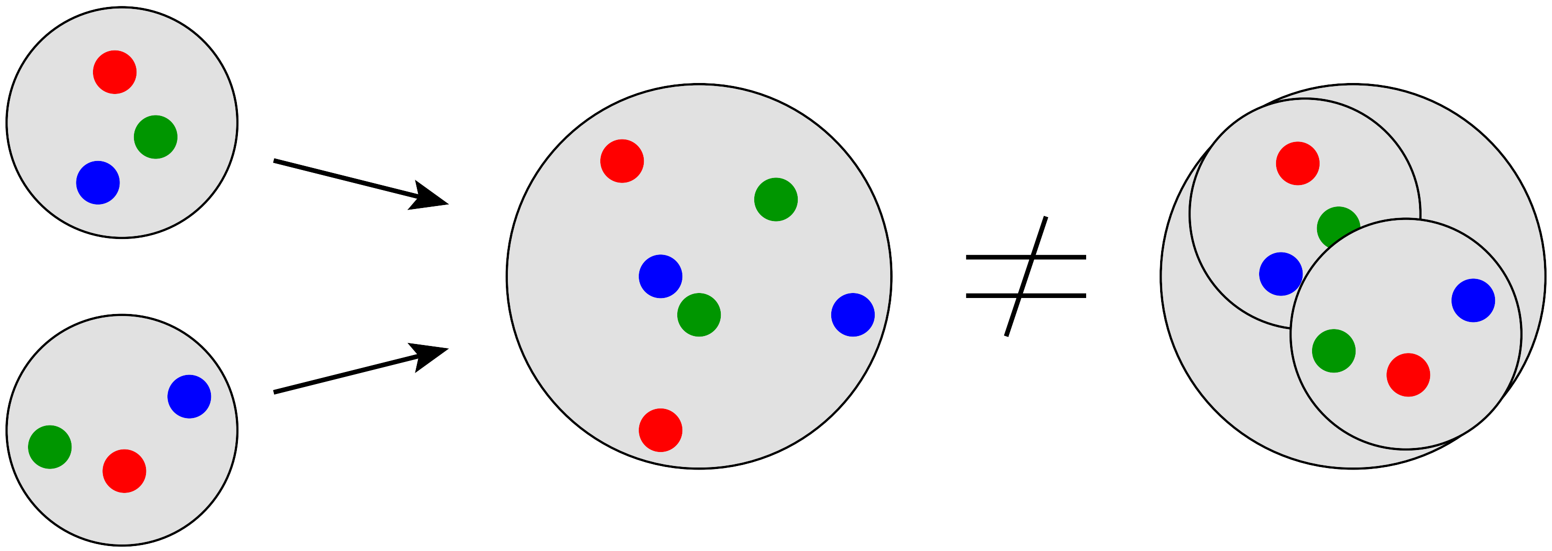
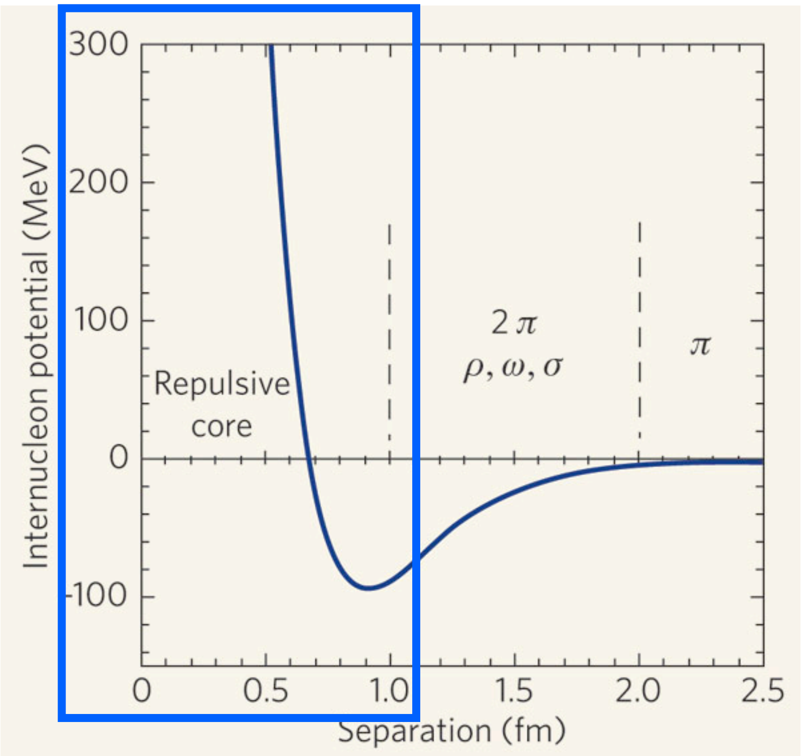
Where are the gluons?



White et al., PRD**49** (1994)

Overlapping Nucleons and Hidden Color





- When $\Delta r < 1\ fm$, the nucleons overlap strongly.

➡ Six valence quarks need not factorize into 2 color-singlet bags.

- $SU(3)_c$ contains many 6-quark "hidden color" states which do not factorize into 2 color-singlet bags

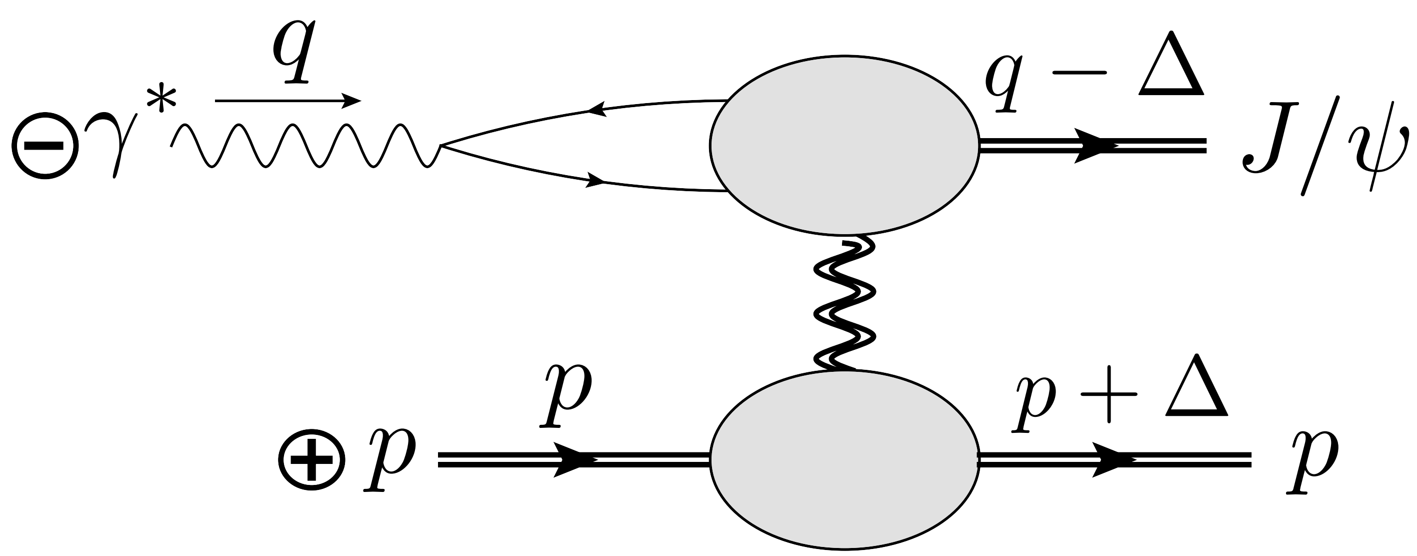
e.g.) symmetric orbital state $$|6q\rangle = \sqrt{\tfrac{1}{9}}|NN\rangle + \sqrt{\tfrac{4}{45}}|\Delta\Delta\rangle + \boxed{\sqrt{\tfrac{4}{5}}|CC\rangle}$$ 80%!

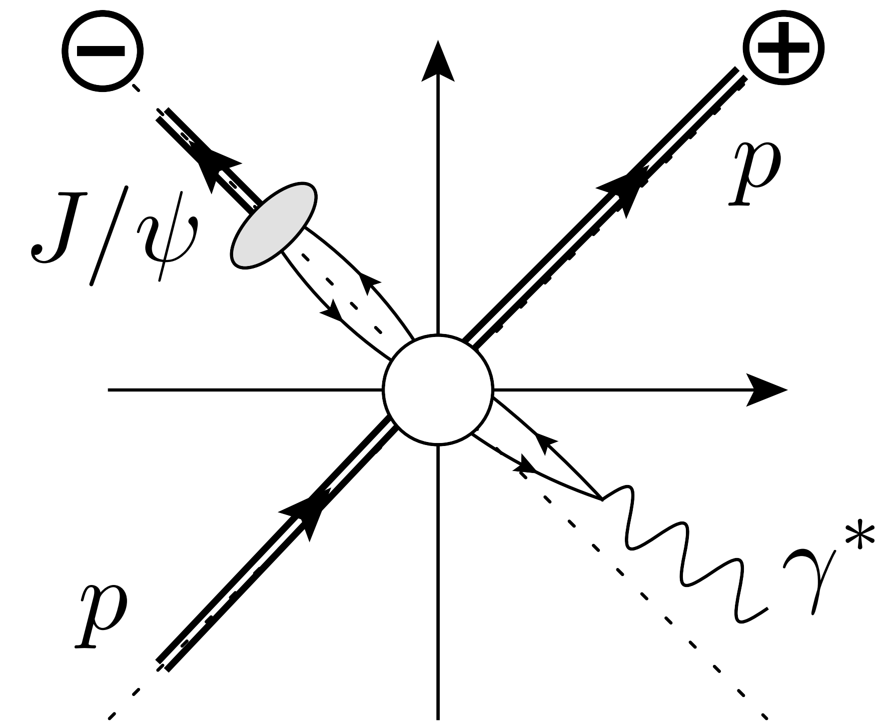
M. Harvey, NPA **352** (1981)

II. The Proposal:

Connecting Diffraction to the NN Potential

Hard Exclusive Meson Production (HEMP)





- Exclusive vector meson production in DIS at small x:

$$s = W^2 = (p+q)^2 \qquad x_{eff} = \frac{Q^2+M_V^2}{s} \ll 1 \qquad T \equiv \Delta^2 \approx -\Delta_T^2$$

- Virtual photon dissociates into a vector meson (e.g. J/ψ) with a hard scale: Q^2 or M_V^2.

- Diffractive scattering: proton intact + rapidity gap

- Meson production in DIS was measured with good statistics at HERA.

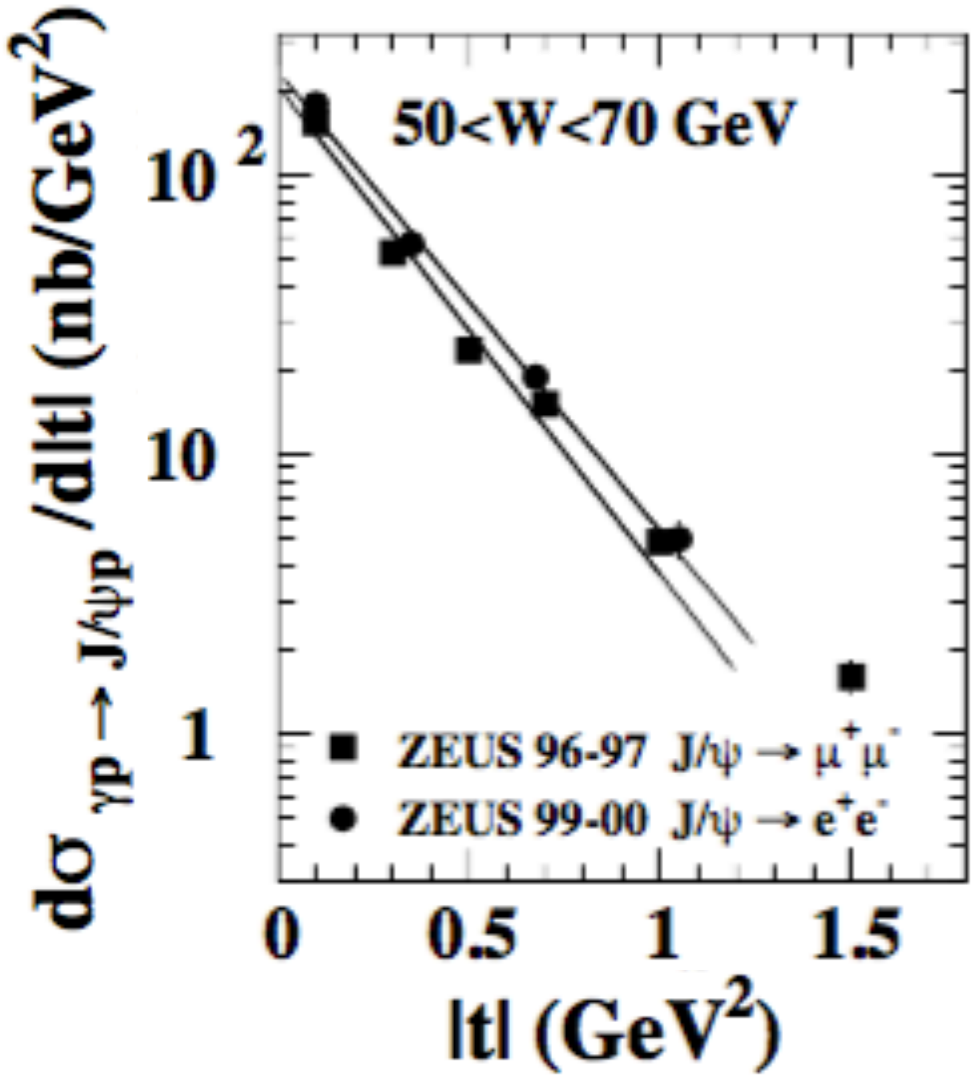
➡ J/ψ decays to electrons, muons

➡ Muon dataset contains $38\ pb^{-1}$ of data out to $|t| = 1.5\ GeV^2$.

➡ Exponential falloff with t:

$$\frac{d\sigma}{dt} = \left.\frac{d\sigma}{dt}\right|_{t=0} e^{bt}$$

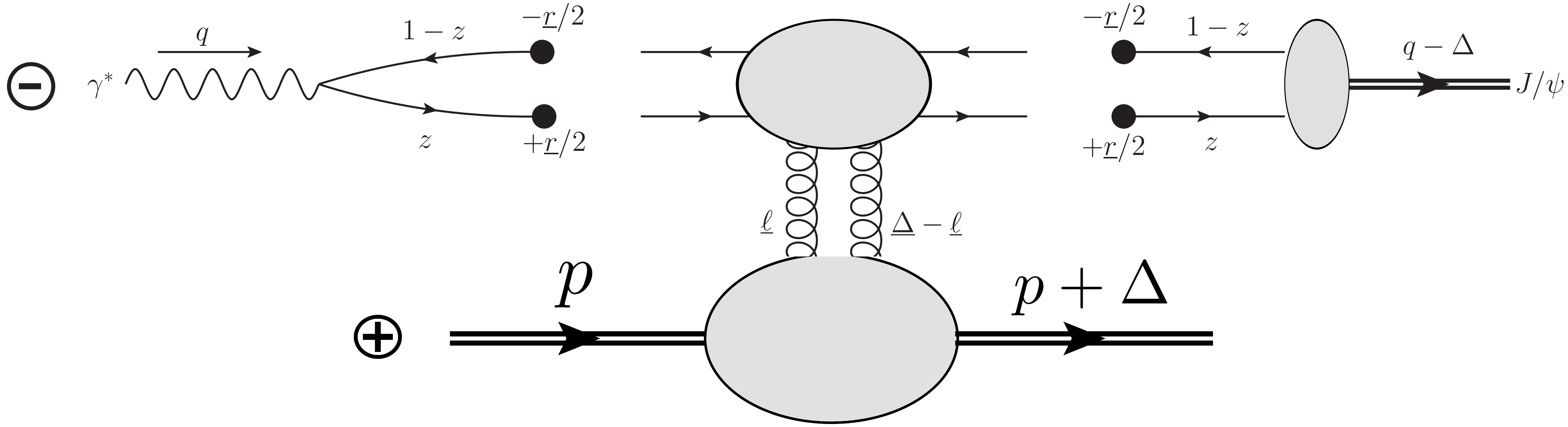
J/ψ photoproduction at ZEUS



Chekanov et al., 0201043

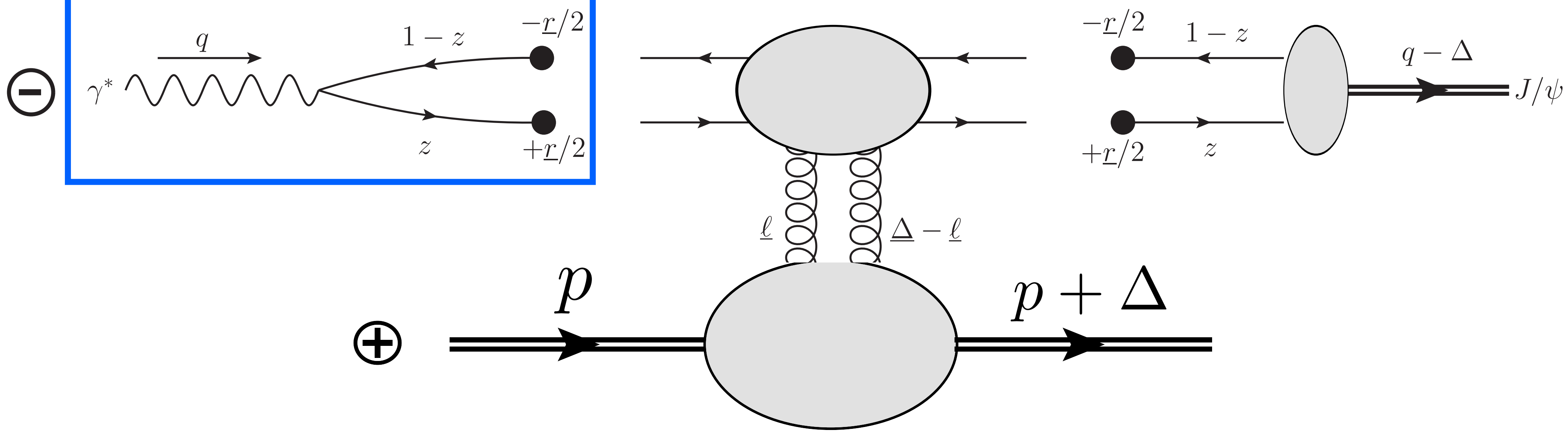
W (GeV)	Mode	N_{obs}	σ (nb)	$\frac{d\sigma}{dt}\|_{t=0}$ (nb/GeV^2)	b (GeV^{-2})
50-70	$\mu^+\mu^-$	1512	$55.8 \pm 1.5 \pm 4.6$	$208 \pm 11^{+24}_{-16}$	$4.02 \pm 0.15^{+0.26}_{-0.14}$

The Gluon Generalized Parton Distribution



The Gluon Generalized Parton Distribution

$$\frac{\Delta x^-_{q\bar{q}}}{q^-} \sim \frac{1}{Q^2}, \frac{1}{m_q^2}$$



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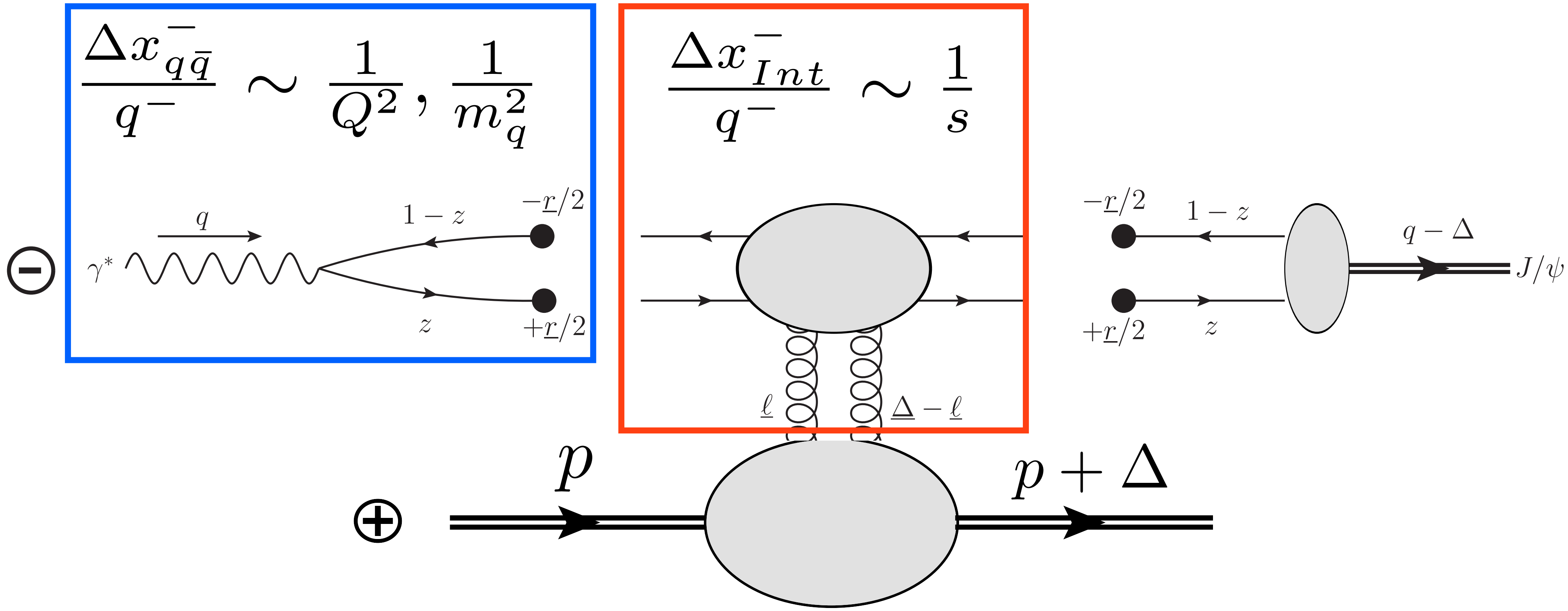

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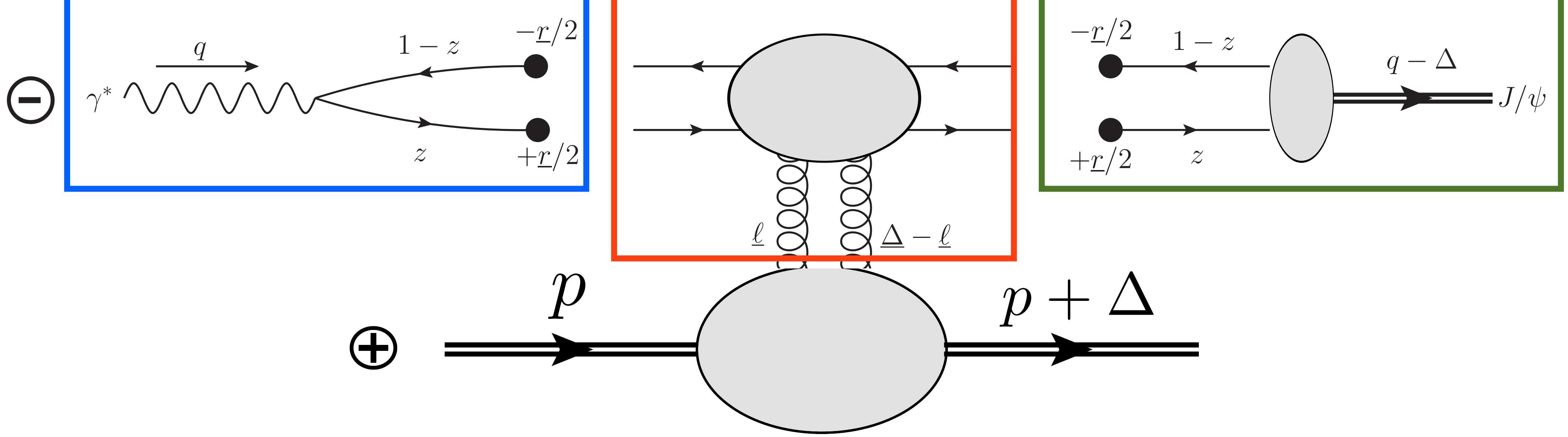
$$\frac{\Delta x^-_{q\bar{q}}}{q^-} \sim \frac{1}{Q^2}, \frac{1}{m_q^2}$$

$$\frac{\Delta x^-_{Int}}{q^-} \sim \frac{1}{s}$$

$$\frac{\Delta x^-_{J}}{q^-} \sim \frac{1}{M_J^2}$$



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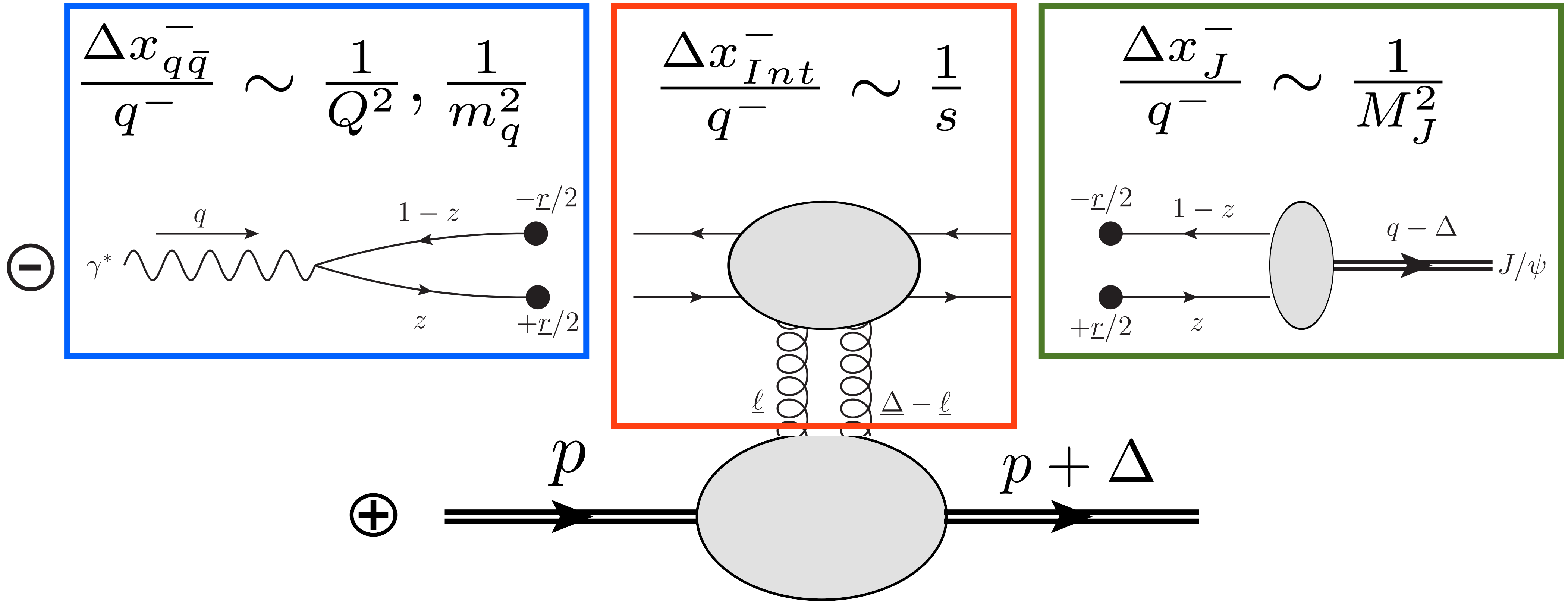
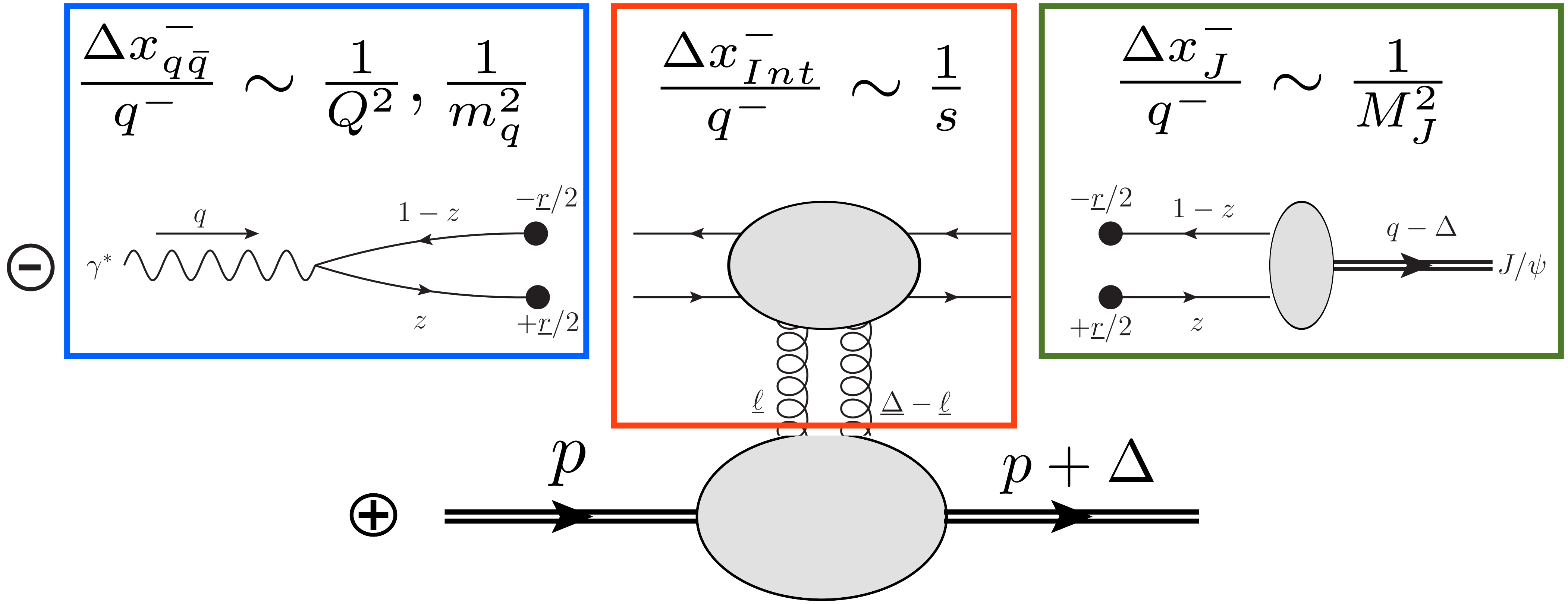


- Separation of <u>time scales</u>: $\Delta x^-_{Int} \ll \Delta x^-_{q\bar{q}} \;,\; \Delta x^-_{J}$

- Transverse <u>length scales</u>: $r_T^2 < \frac{1}{Q^2 + m_q^2} \longrightarrow r_T^2 \ll \frac{1}{\Lambda^2_{QCD}}$

The Gluon Generalized Parton Distribution



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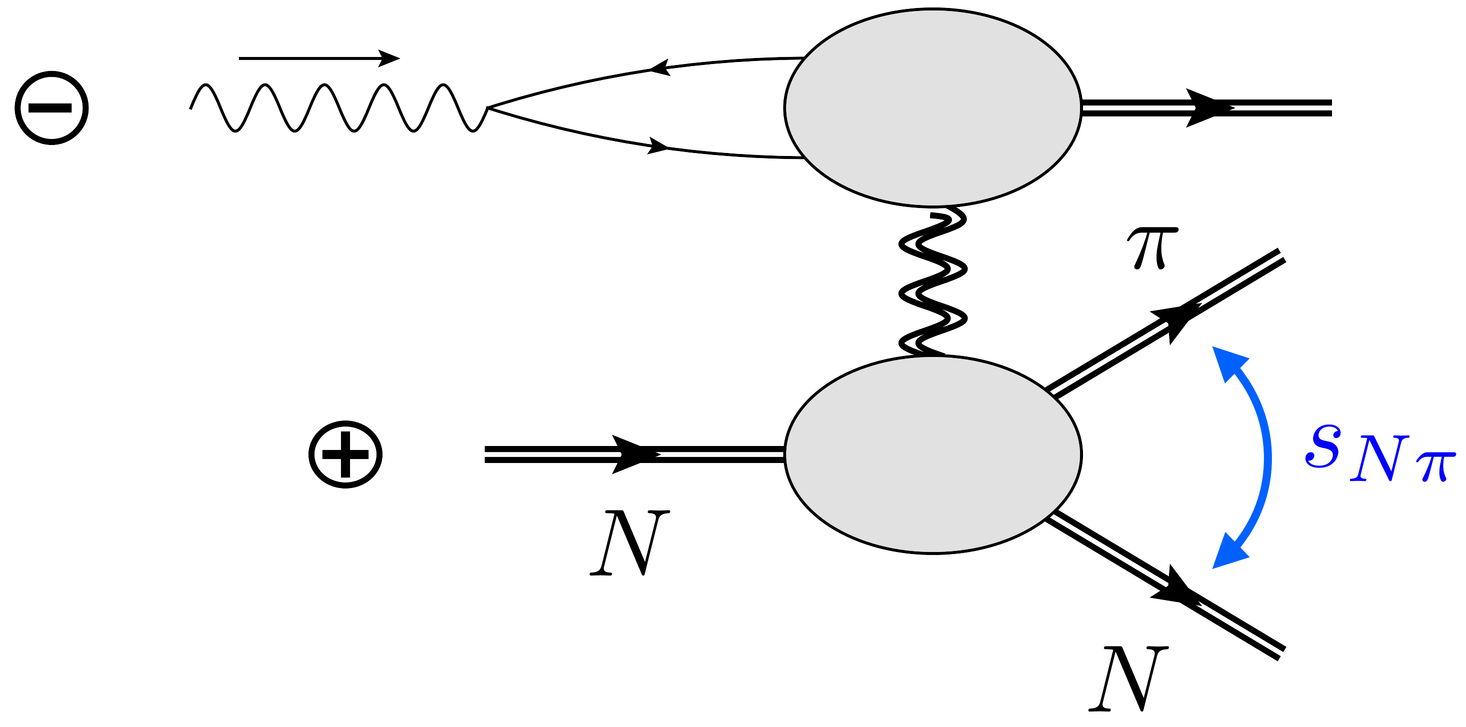
- Transverse length scales: $r_T^2 < \frac{1}{Q^2+m_q^2} \longrightarrow r_T^2 \ll \frac{1}{\Lambda^2_{QCD}}$
- Small dipole measures a snapshot of the gluon field (GPD)

$$H^g(x,\xi,T) = \int \frac{dr^-}{2\pi p^+} e^{ixp^+r^-} \left\langle p+\tfrac{1}{2}\Delta\right| \underline{F^{+ia}(-\tfrac{1}{2}r)F^{+ia}(+\tfrac{1}{2}r)} \left|p-\tfrac{1}{2}\Delta\right\rangle$$

Multi-Particle Targets: “Transition GPD’s”

Goeke, Polyakov, Vanderhaeghen 0106012 M. Diehl 0307382



- The factorization theorem for HEMP covers a wide range of processes, including when the final state differs from the initial state.

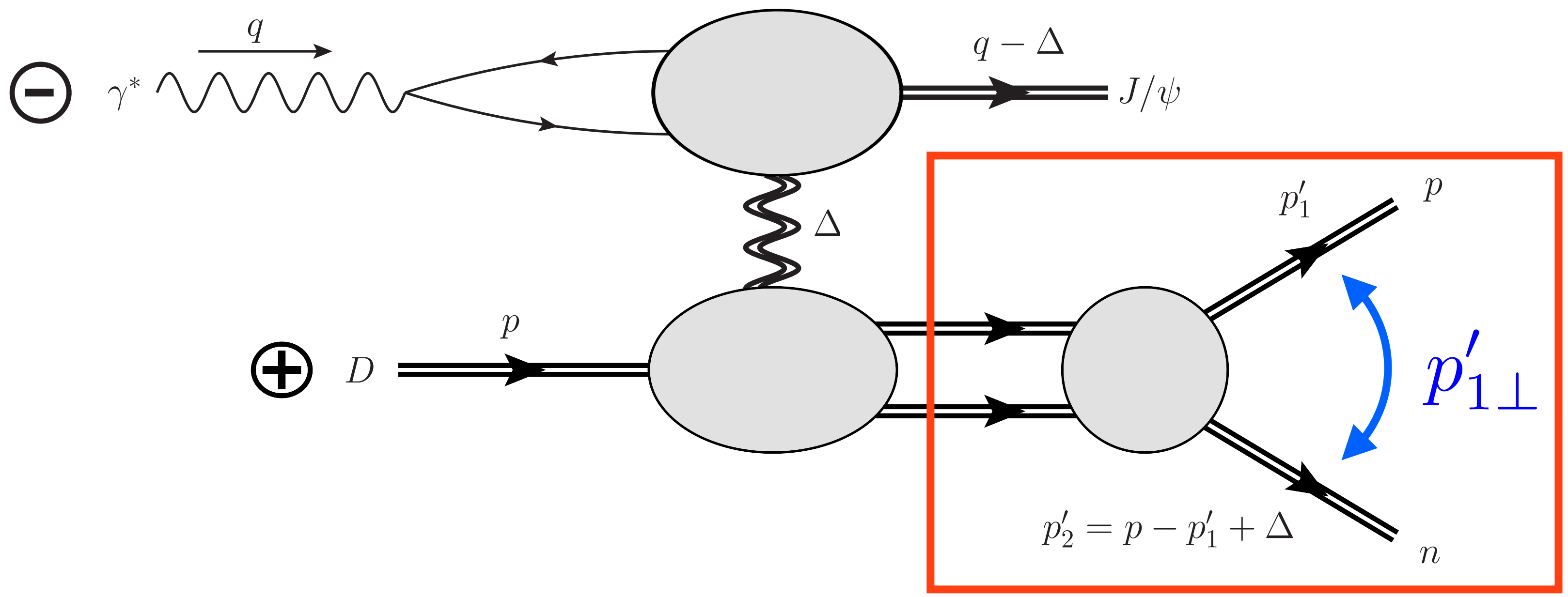
➡ “Transition GPD’s” depend on additional kinematic variables

$$\langle N\pi | F^{+ia} F^{+ia} | N \rangle$$

➡ Factorization holds for “low-mass” final states

$$Q^2 \gg s_{N\pi} \, , \, \Lambda^2_{QCD}$$

A "Back Door" to Short-Range NN Interactions

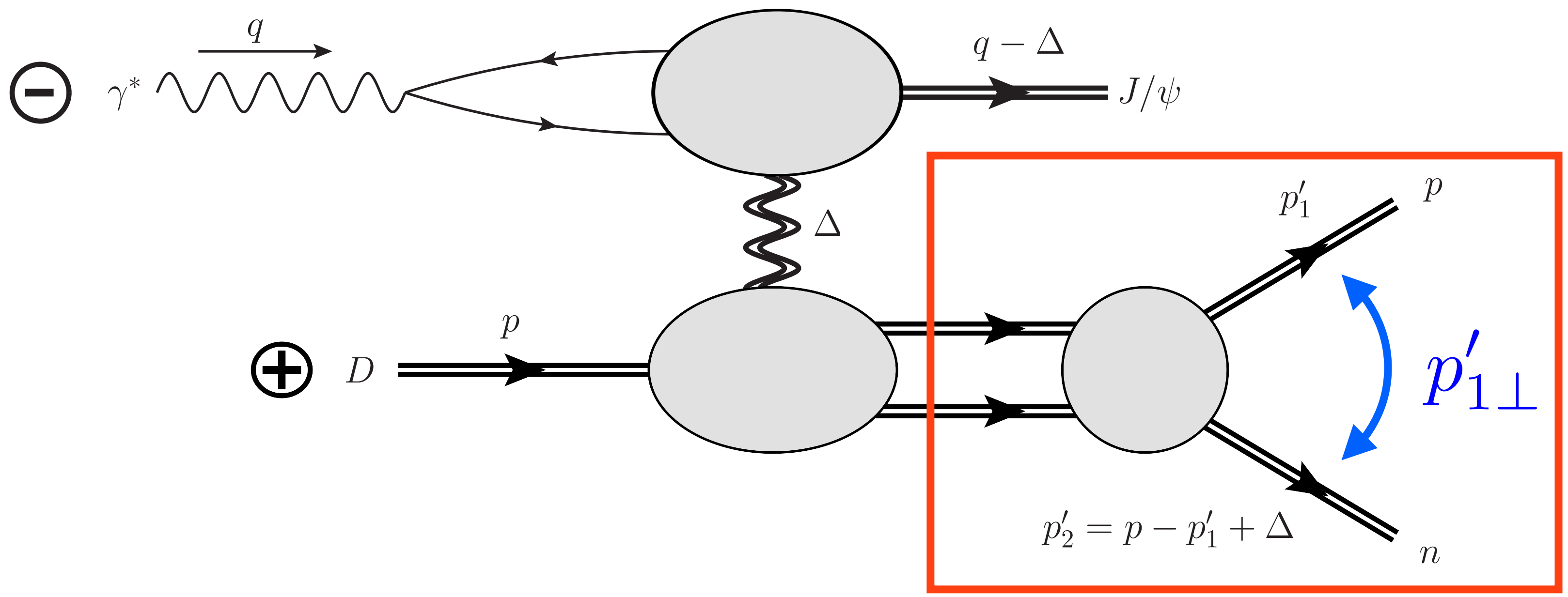


- Our proposal: A different way to access high-energy NN scattering at an EIC.

$$e + D \to e + J/\psi + p + n$$

➡HEMP off a deuteron target at small x

➡Deuteron disintegrates into a proton / neutron pair



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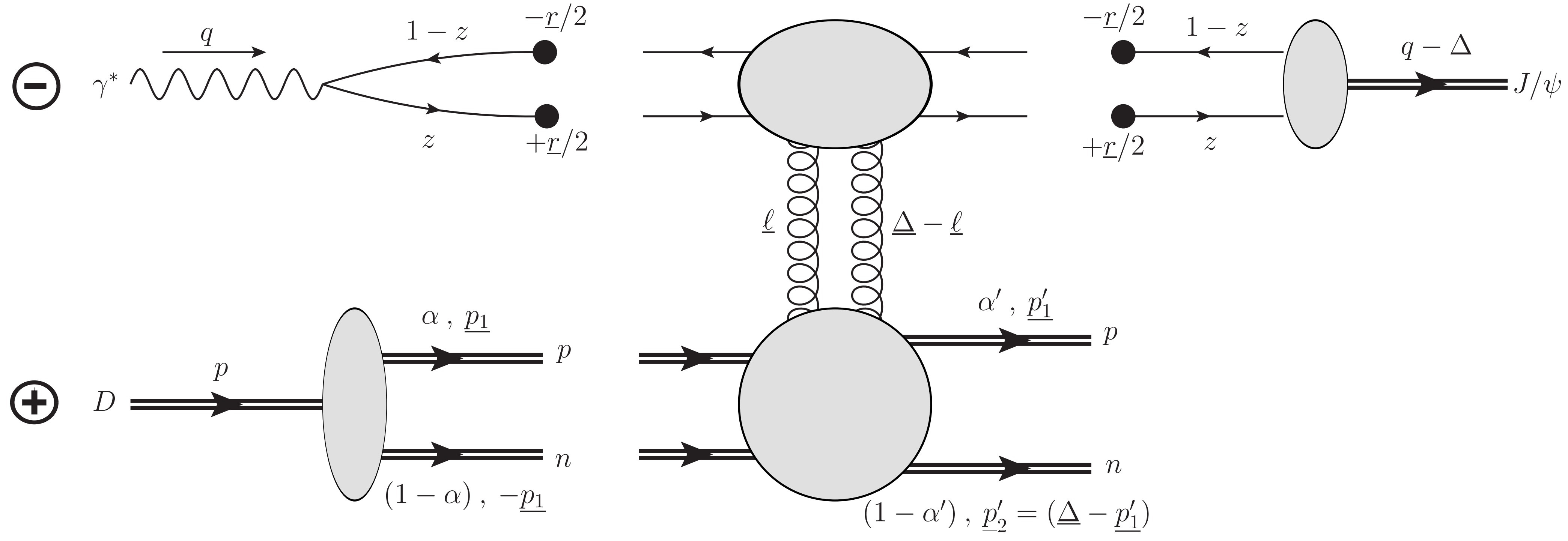
Key Concept: At high NN transverse momentum, can factorize a short-distance NN rescattering

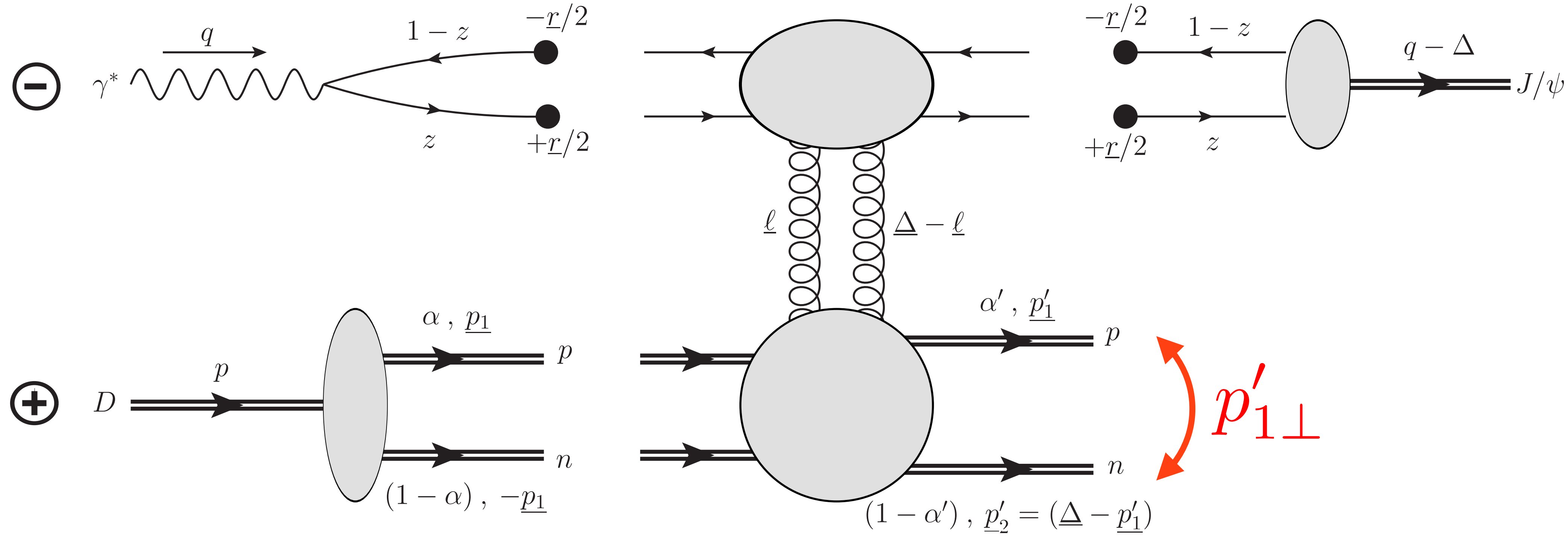
HEMP on the Deuteron



- Deuteron target: same formalism, but composite system.

➡ Loosely bound deuteron: predominantly NN wave function

➡ Gluon exchange essentially occurs on an NN target.



- **Deuteron target**: same formalism, but composite system.

➡ Loosely bound deuteron: predominantly NN wave function

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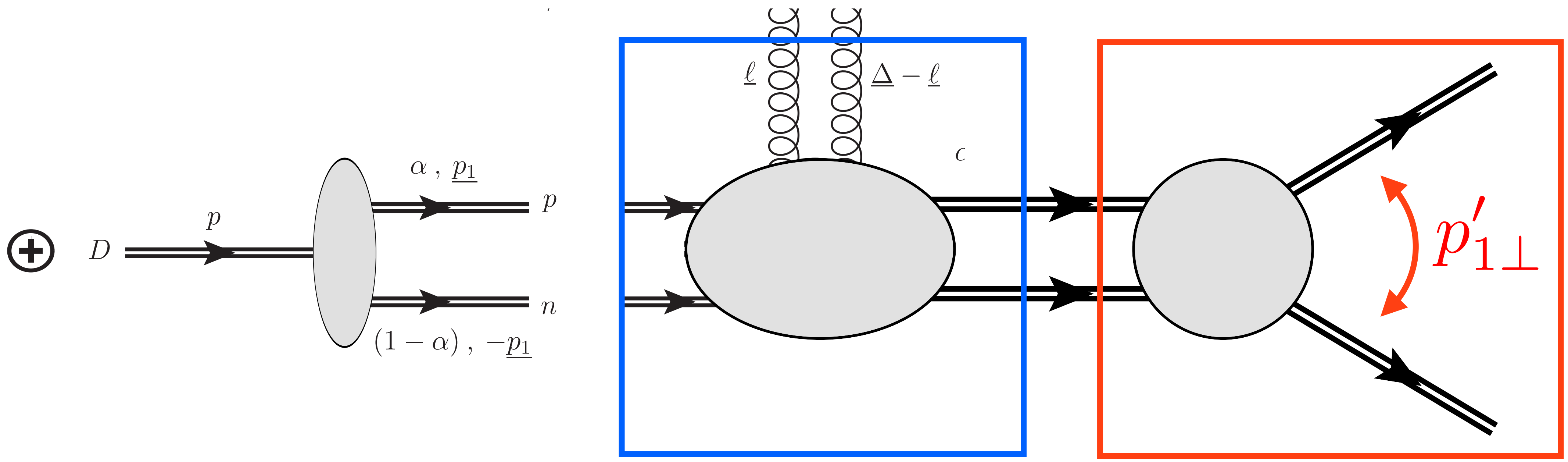
- Deuteron dissociates into a p n final state (transition GPD)

$$\hat{H}^g_{(D)} = \int \frac{dr^-}{2\pi p^+} e^{ixp^+r^-} \underline{\langle p\, n\, (p'_{1\perp})|} F^{+ia}(-\tfrac{1}{2}r) F^{+ia}(+\tfrac{1}{2}r) \underline{|D\rangle}$$

A Lever to Extract NN Rescattering

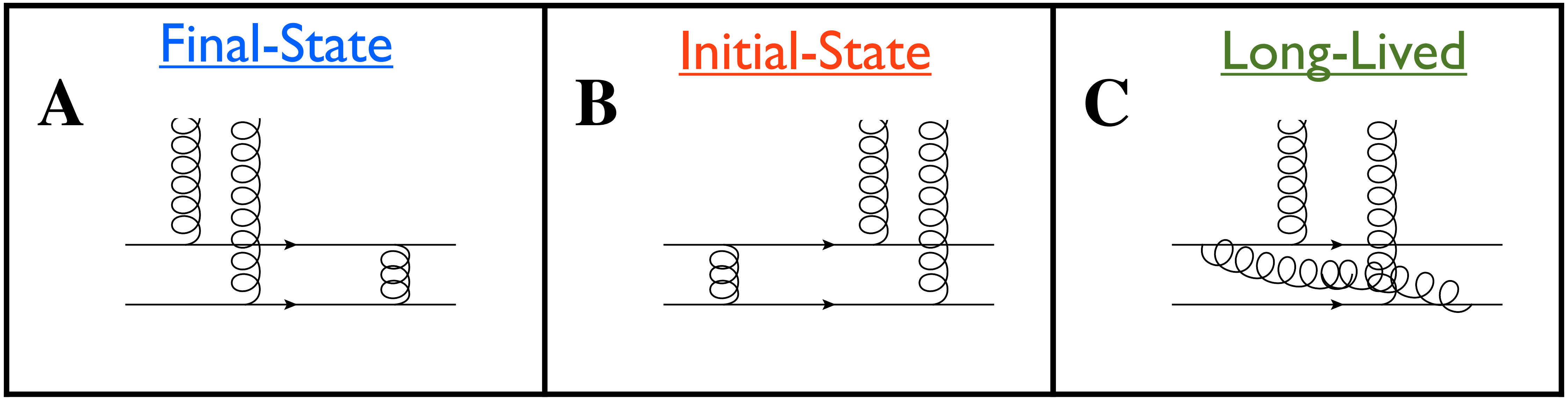


$$\langle N' \, N' | F^{+ia} F^{+ia} | N \, N \rangle \otimes \langle p \, n \, (p'_{1\perp}) | \, V \, | N' \, N' \rangle$$

- When $p'_{1\perp}$ becomes a hard scale, it should lead to a factorization of the T-GPD itself!
  - ➡ Dipole scatters in the gluon field of the nucleons $\quad s_{NN} \approx 4 p'^2_{1T}$
  - ➡ An additional hard NN scattering occurs at lower energy: $\quad Q^2 \gg s_{NN} \gg \Lambda^2_{QCD}$

III. Proof of Principle:

Calculations for the Quark Target Model

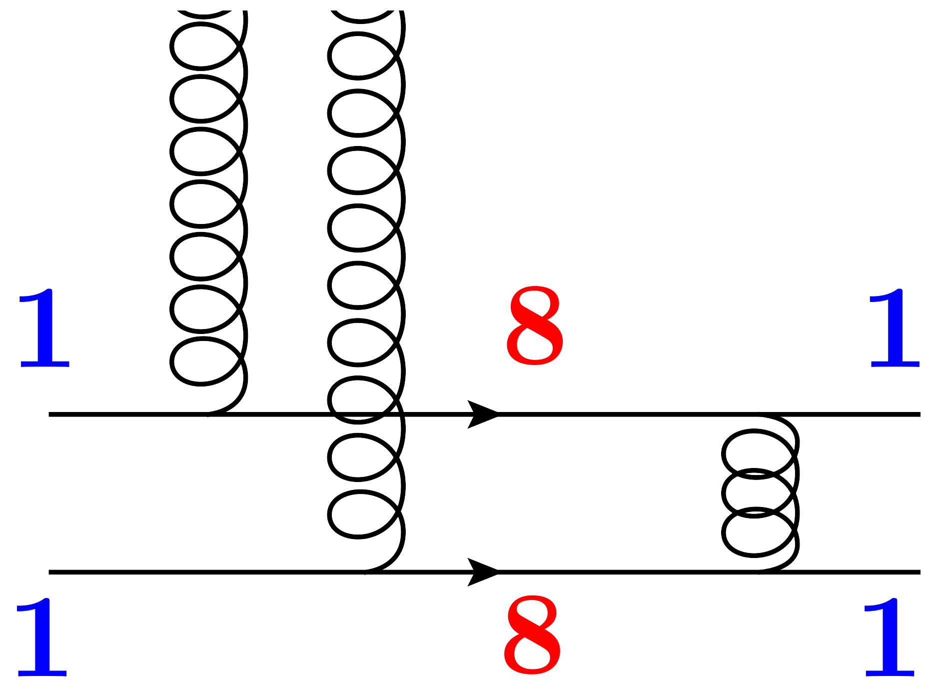


- **Quark Target Model:**
  - ➡ Treat the nucleons as single quarks in pQCD.
  - ➡ Rescattering by single gluon exchange.
- Three distinct topologies:
  - ➡ Final-state interactions
  - ➡ Initial-state interactions
  - ➡ Long-lived fluctuations

The Role of Octet Color Charge

- Quark target: leading-order rescattering is color octet

➡ Cannot occur in isolation.



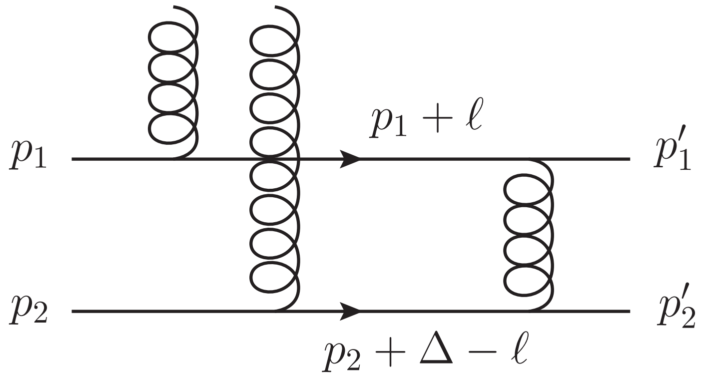
- But it can contribute to the T-GPD!

➡ Rescattering is coupled to the diffractive exchange.

Deuteron breakup is sensitive to "hidden color" content of the short-distance nuclear force!

Quark Target: Numerator Structure

Final-State Interaction



$$[\bar{U}_{\sigma_p'}(p_1')\gamma_\perp^i\gamma^-\gamma^+U_{\sigma_p}(p_1)]\,[\bar{U}_{\sigma_n'}(p_2')\gamma_\perp^i\gamma^-\gamma^+U_{\sigma_p}(p_2)]$$

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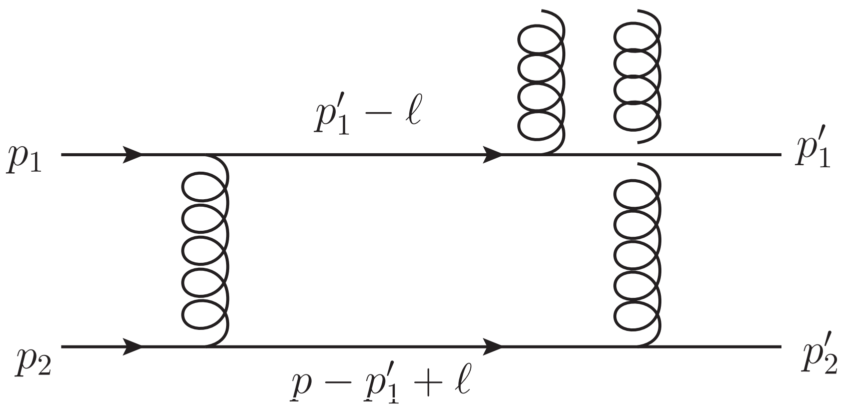

$$[\bar{U}_{\sigma_p'}(p_1')\gamma^+\gamma^-\gamma_\perp^iU_{\sigma_p}(p_1)]\,[\bar{U}_{\sigma_n'}(p_2')\gamma^+\gamma^-\gamma_\perp^iU_{\sigma_n}(p_2)]$$

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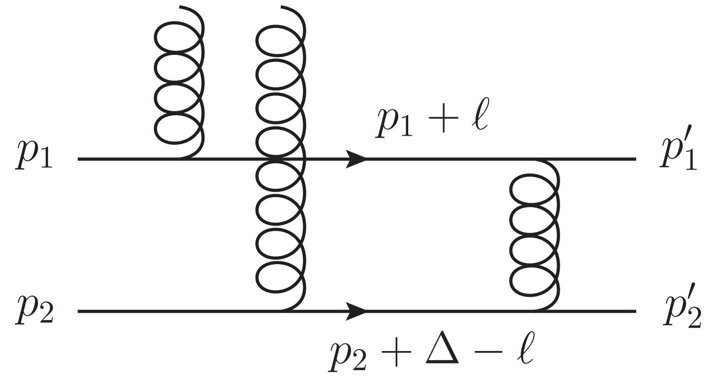

$$[\bar{U}_{\sigma_p'}(p_1')\gamma_\perp^i \gamma^- \gamma^+ U_{\sigma_p}(p_1)]\,[\bar{U}_{\sigma_n'}(p_2')\gamma_\perp^i \gamma^- \gamma^+ U_{\sigma_p}(p_2)]$$

$$\sim \underline{p_{1T}'^2}\,\delta_{\sigma_p,-\sigma_n}$$

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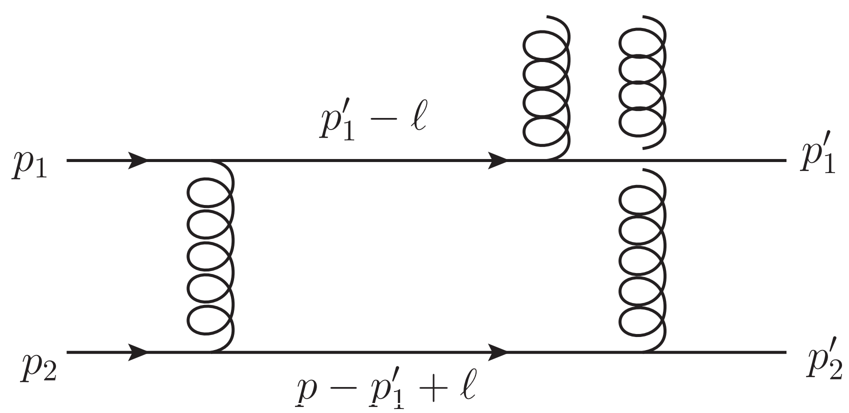

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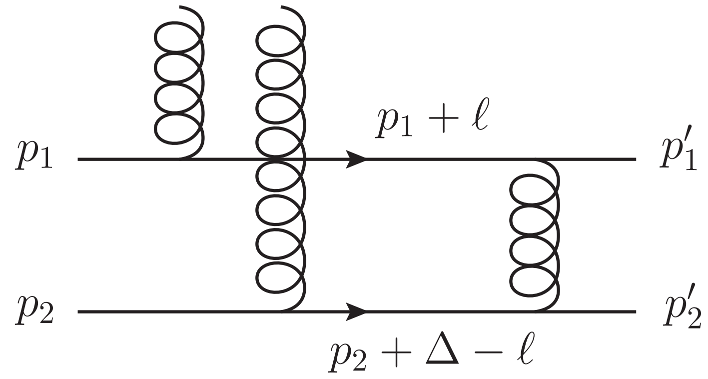
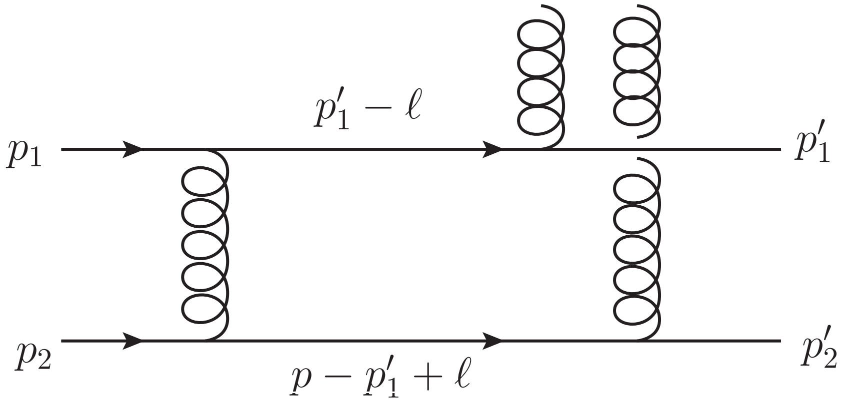


$$[\bar{U}_{\sigma_p'}(p_1')\gamma_\perp^i \gamma^- \gamma^+ U_{\sigma_p}(p_1)]\,[\bar{U}_{\sigma_n'}(p_2')\gamma_\perp^i \gamma^- \gamma^+ U_{\sigma_p}(p_2)]$$

$$\sim \underline{p_{1T}'^2}\, \delta_{\sigma_p, -\sigma_n} \quad \Rightarrow \quad \underline{(S_D)_z = 0}$$

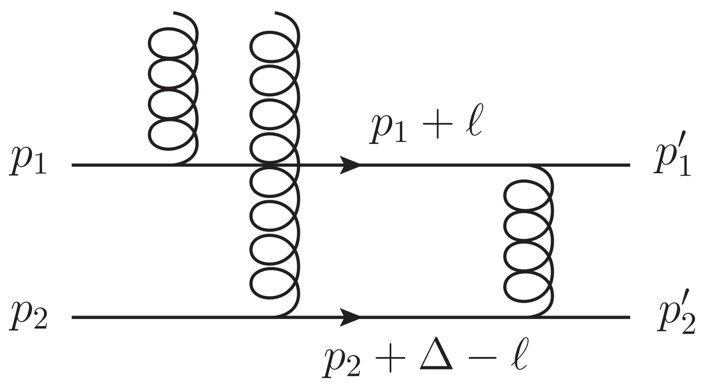
Initial-State Interaction



$$[\bar{U}_{\sigma_p'}(p_1')\gamma^+ \gamma^- \gamma_\perp^i U_{\sigma_p}(p_1)]\,[\bar{U}_{\sigma_n'}(p_2')\gamma^+ \gamma^- \gamma_\perp^i U_{\sigma_n}(p_2)]$$

Quark Target: Numerator Structure

Final-State Interaction



$$\left[\bar{U}_{\sigma_p'}(p_1')\gamma_\perp^i \gamma^- \gamma^+ U_{\sigma_p}(p_1)\right] \left[\bar{U}_{\sigma_n'}(p_2')\gamma_\perp^i \gamma^- \gamma^+ U_{\sigma_p}(p_2)\right]$$

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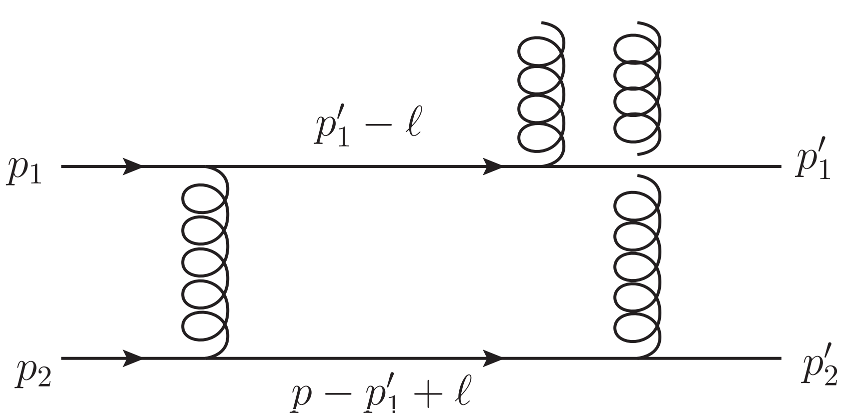
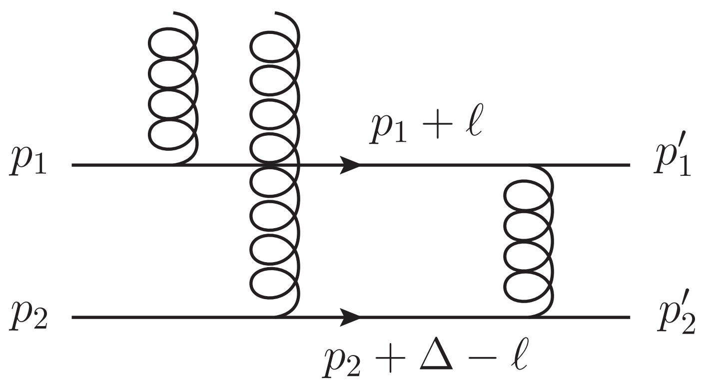


$$\left[\bar{U}_{\sigma_p'}(p_1')\gamma^+ \gamma^- \gamma_\perp^i U_{\sigma_p}(p_1)\right] \left[\bar{U}_{\sigma_n'}(p_2')\gamma^+ \gamma^- \gamma_\perp^i U_{\sigma_n}(p_2)\right]$$

$$\propto \underline{m_N^2}$$

Quark Target: Numerator Structure

Final-State Interaction



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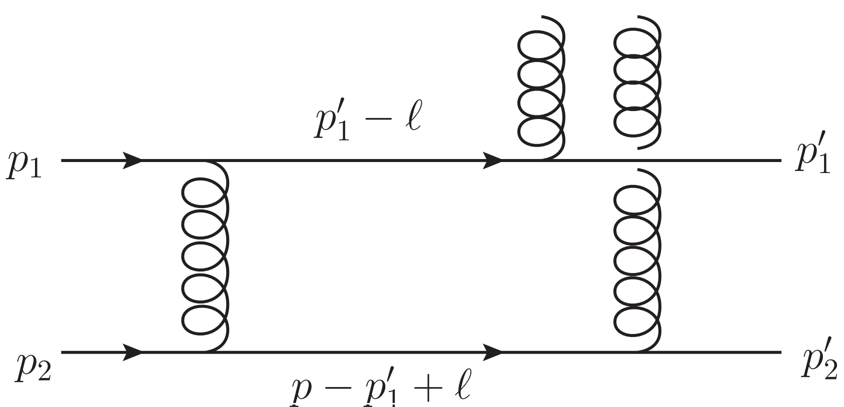
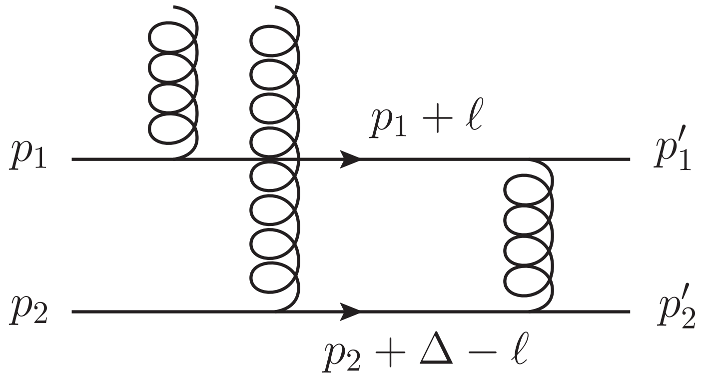


$$[\bar{U}_{\sigma_p'}(p_1')\gamma^+ \gamma^- \gamma_\perp^i U_{\sigma_p}(p_1)]\, [\bar{U}_{\sigma_n'}(p_2')\gamma^+ \gamma^- \gamma_\perp^i U_{\sigma_n}(p_2)]$$

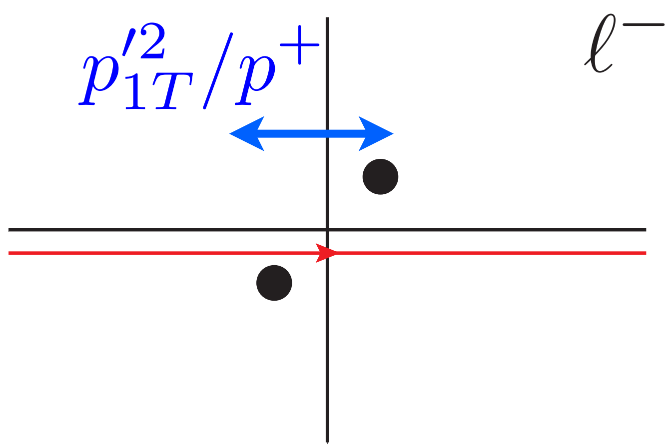
$$\propto \underline{m_N^2} \quad ➡ \quad \underline{\text{suppressed}}$$

Quark Target: Pole Structure

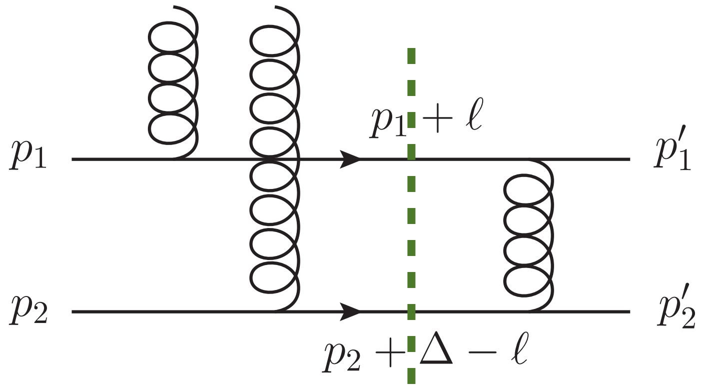
Final-State Interaction



$$\left[\frac{1}{\ell^- - m_N^2/p_1^+ \underline{+ i\epsilon}}\right] \left[\frac{1}{\ell^- - s_{NN}/p_2^+ \underline{- i\epsilon}}\right]$$



Final-State Interaction



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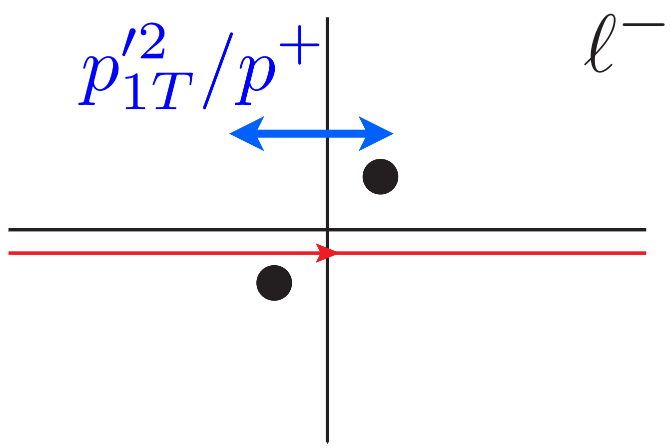
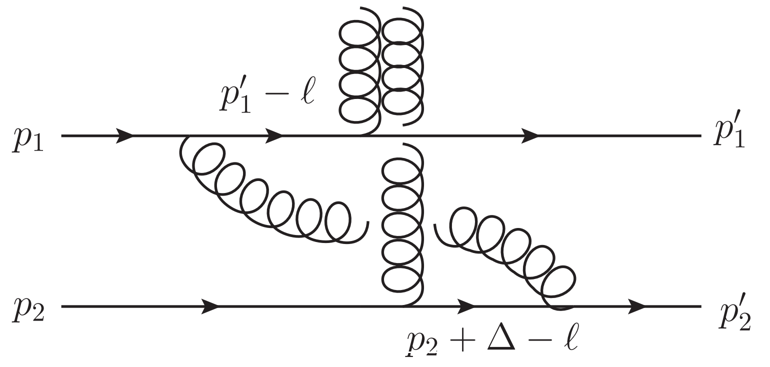
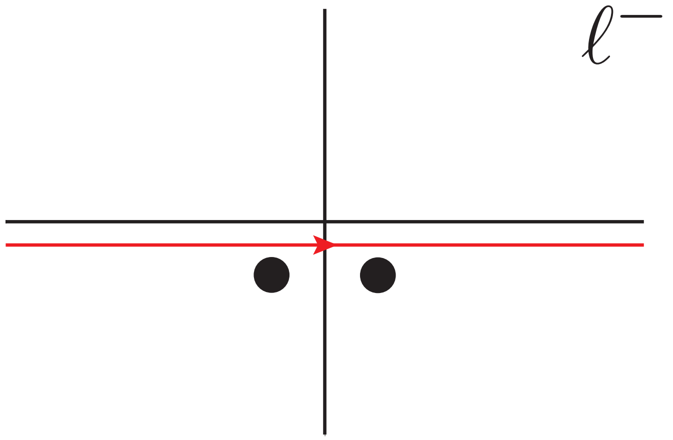


- Poles of loop integral are pinched
  - ➡ Virtuality $\sim p_{1T}'^2$
  - ➡ Lifetime $\sim 1/p_{1T}'$
  - ➡ Equivalent to the energy denominator in light-front perturbation theory

"Long-Lived" Fluctuations





- Potentially dangerous "factorization breaking" terms.

$$\left[\frac{1}{\ell^- - m_N^2 / p_1^+ - i\epsilon} \right] \left[\frac{1}{\ell^- - s_{NN} / p_2^+ - i\epsilon} \right]$$

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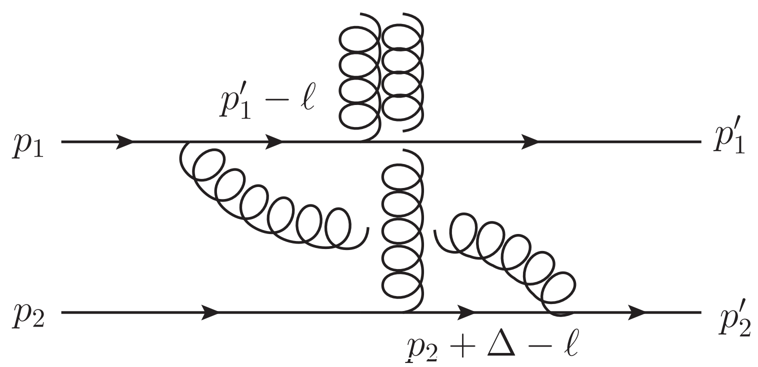

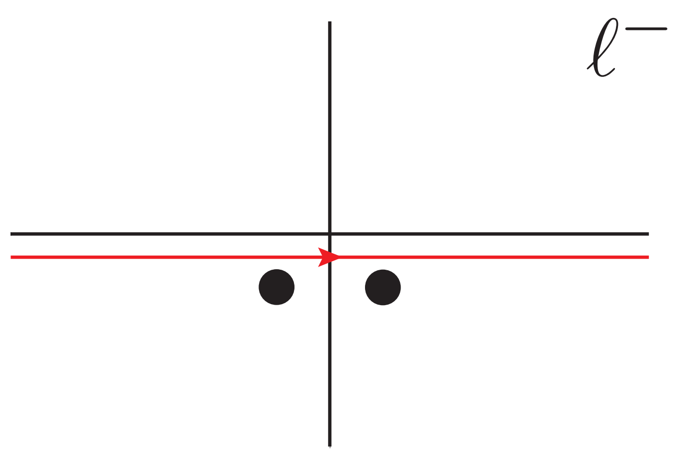

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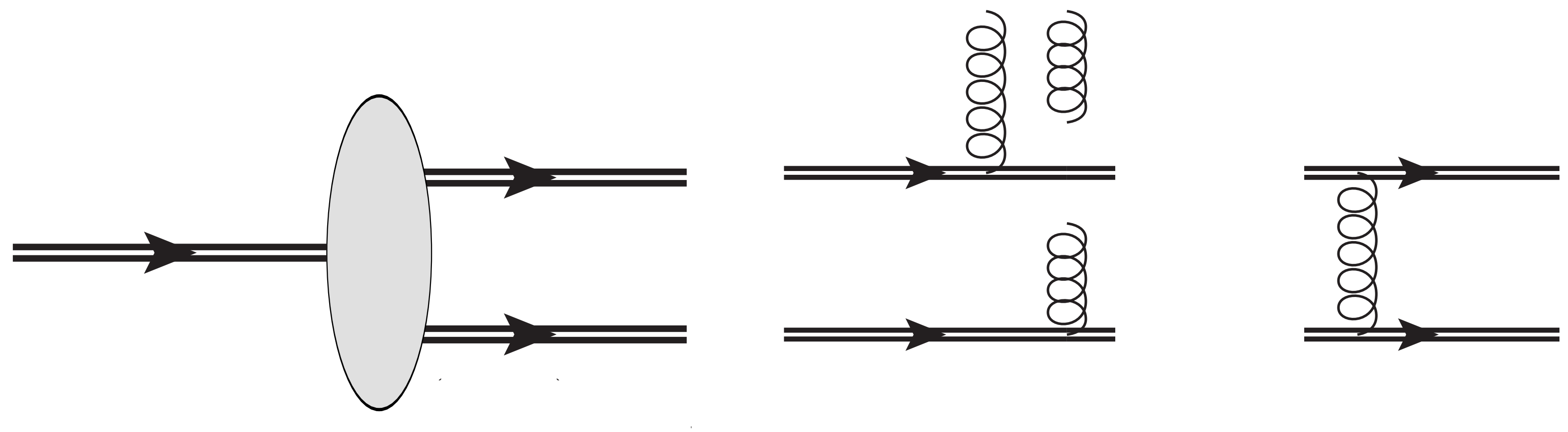
$$\left[\frac{1}{\ell^- - m_N^2/p_1^+ \underline{- i\epsilon}} \right] \left[\frac{1}{\ell^- - s_{NN}/p_2^+ \underline{- i\epsilon}} \right]$$

➡ Pinch is broken (same side of real axis)

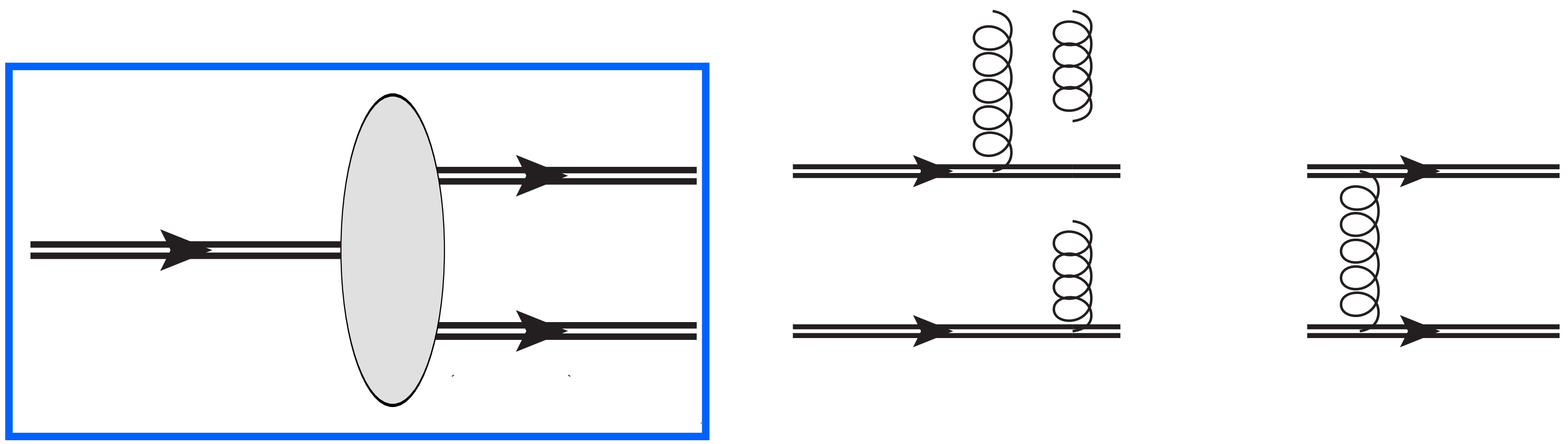
➡ Interaction is zero in the eikonal approximation

➡ Suppressed

Lessons of the Quark Target Model



$$\hat{H}^g_{(D)} \approx \psi_D(r_\perp = 0, x = \tfrac{1}{2}, S_z = 0)\, 2\frac{\alpha_s}{N_c} H^g_{(N)}\, \frac{1}{p'^2_{1T}}$$



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- Short distance component of deuteron WF.

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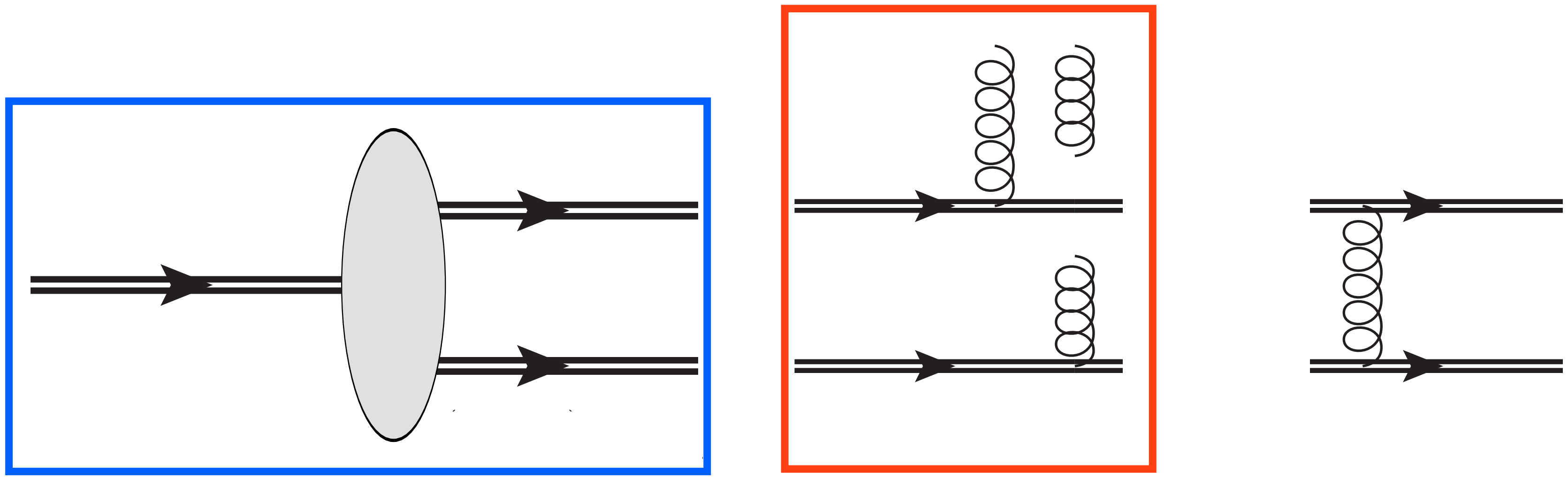

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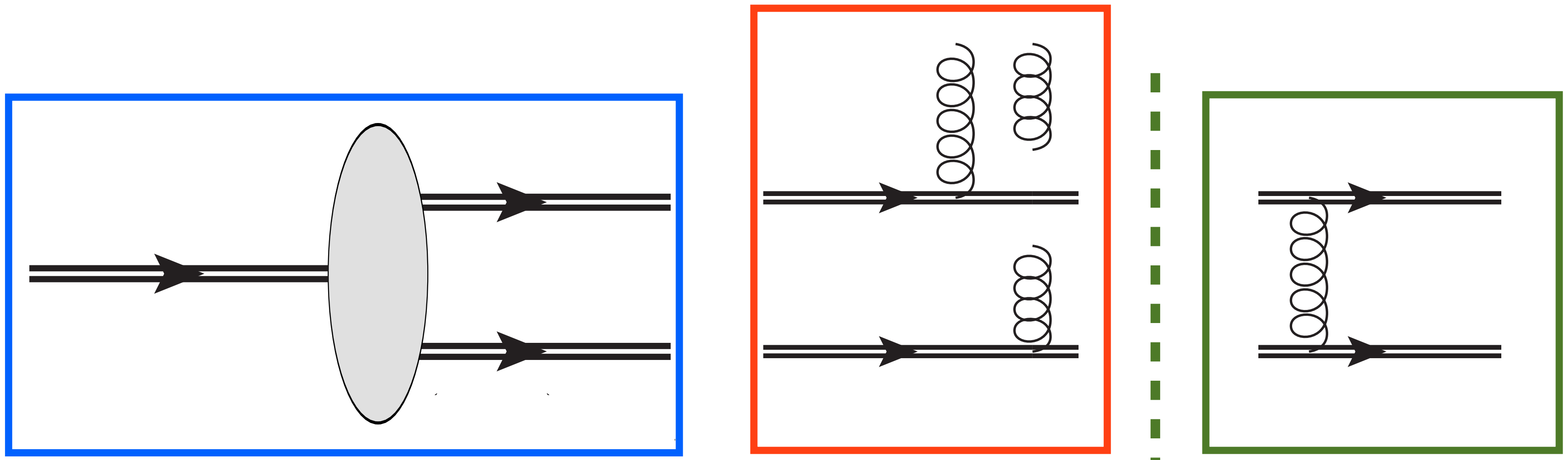
- Short distance component of deuteron WF.
- Diffraction occurs on the NN system (model dependent).



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- Short distance component of deuteron WF.
- Diffraction occurs on the NN system (model dependent).
- Pole structure is robust:
  - ➡ FSI dominate with a lifetime of $\sim 1/p'_{1T}$
  - ➡ ISI are suppressed
  - ➡ LLF are un-pinched

Applying the Quark Target Model Literally

$$\frac{d\sigma^{\gamma D \to V N N}}{dT\, dt\, dy} = \left[\frac{1}{12\pi} \frac{\alpha_s^2}{N_c^2} \frac{1}{p'^4_{1T}} \left| \psi_D (0_\perp , \tfrac{1}{2}) \right|^2 \right] \times \frac{d\sigma^{\gamma N \to V N}}{dT}$$

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$$\frac{d\sigma^{\gamma D \to V N N}}{dT\, dt\, dy} = \left[\frac{1}{12\pi} \frac{\alpha_s^2}{N_c^2} \frac{1}{p_{1T}'^4} \left| \psi_D(0_\perp, \tfrac{1}{2}) \right|^2 \right] \times \frac{d\sigma^{\gamma N \to V N}}{dT}$$

- ➡ Use ZEUS fit to J/ψ photoproduction with $|T| \approx 0.04\ GeV^2$
- ➡ $\psi_D(0_\perp, \frac{1}{2}) \approx 1.05\ fm^{-1}$ (Reid93 , Nijmegen II)
- ➡ $\alpha_s \approx 0.3 \quad N_c = 3$

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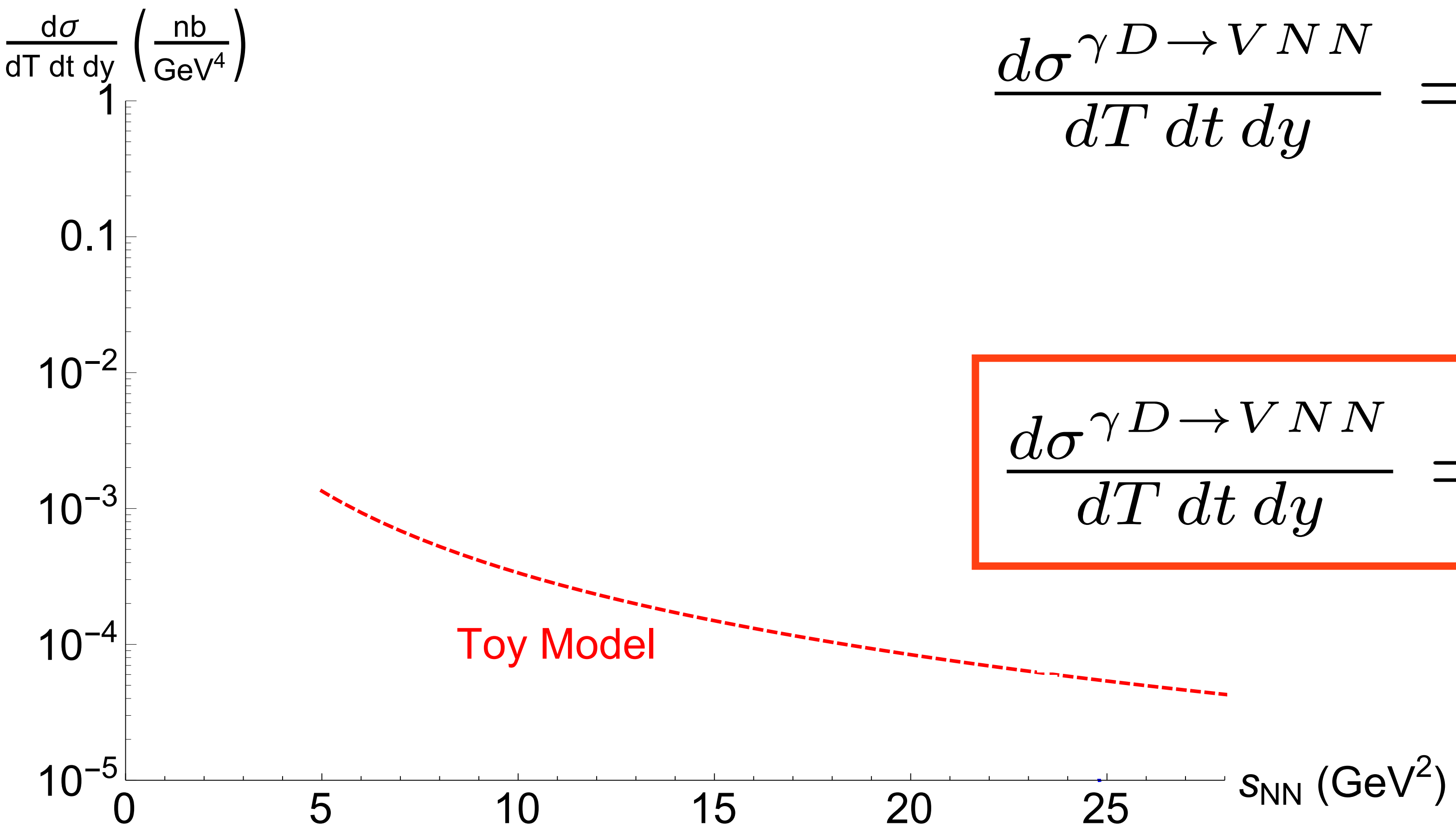

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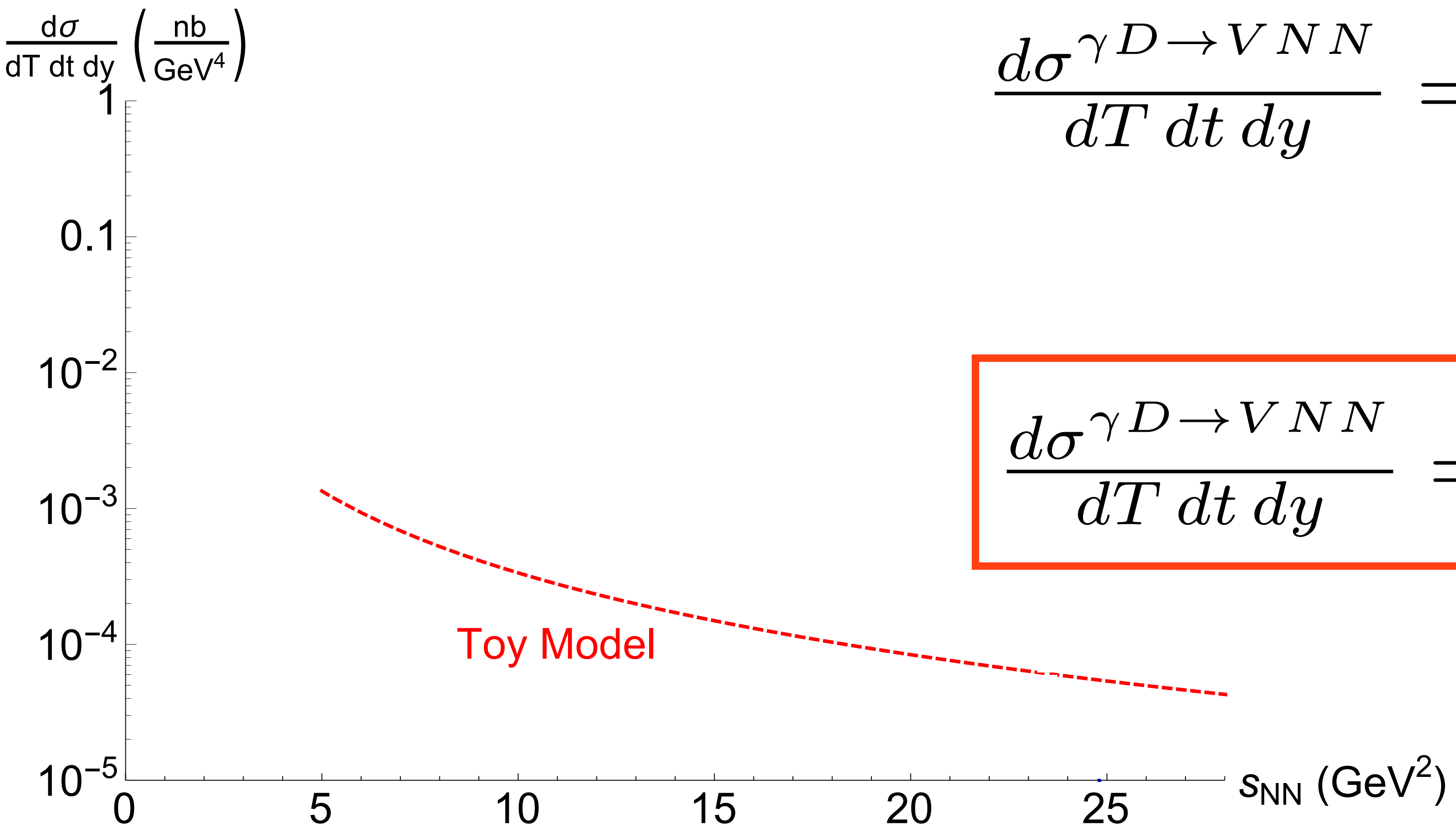

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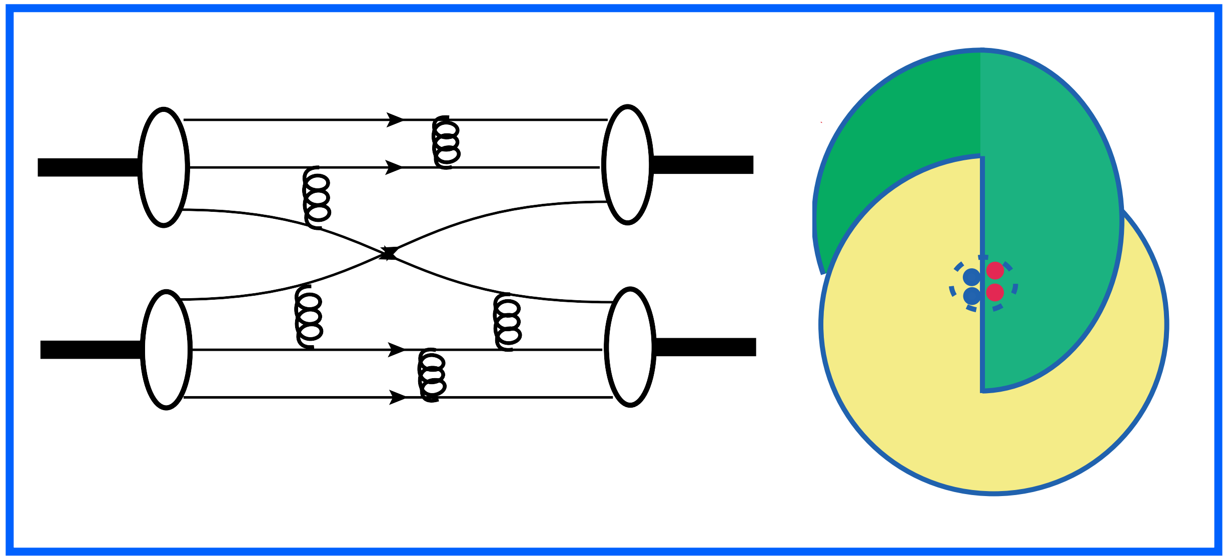
- pQCD rescattering: small magnitude, but slow falloff.
- Difficult, but within the reach of an EIC.

IV. Feasibility:

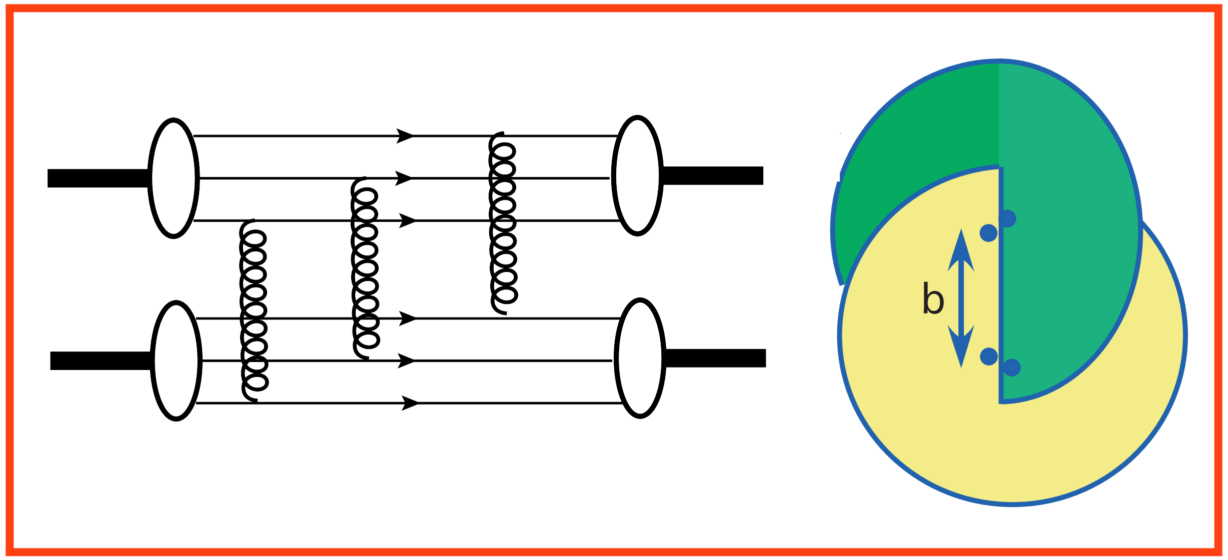
Realistic Nucleons at an EIC

Considerations for Realistic Nucleons

Brodsky-Farrar



Landshoff



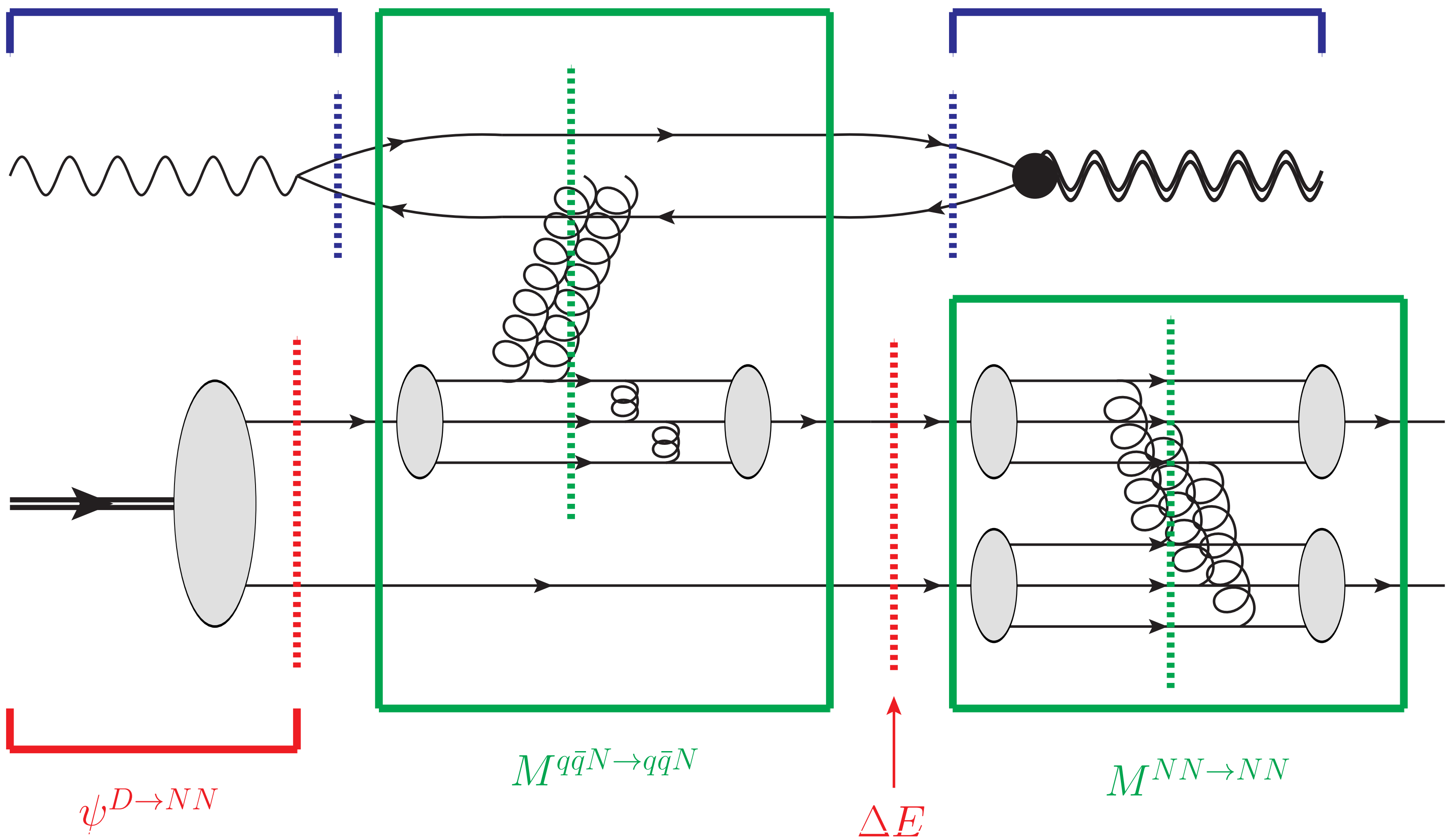
- For realistic nucleons, hard elastic scattering must deliver a hard momentum kick to all 3 valence quarks.

➡ Requires multi-parton exchange (ie, Brodsky-Farrar or Landshoff)

➡ Color singlet channels now contribute at leading order

- General lessons of the Quark Target Model dictate the structure of the amplitude for nucleons.

General Structure for Realistic Nucleons



$$\frac{d\sigma^{\gamma D \to V N N}}{dT\, dt\, dy} \propto |\psi_D(0_\perp, \tfrac{1}{2})|^2 \, |M^{\gamma N \to V N}|^2 \, \frac{1}{(p^+ \Delta E^-)^2} \, |M^{NN \to NN}|^2$$

- For color-singlet FSI, diffraction proceeds on one nucleon with the other nucleon a spectator.

➡ NN rescattering mechanism determines p'^2_{1T} dependence.

Typical Rates for Realistic Nucleons

$$\frac{d\sigma^{\gamma D \to V N N}}{dT\, dt\, dy} = \frac{|\psi_D(0_\perp, \frac{1}{2})|^2}{\pi^2} \frac{d\sigma^{\gamma N \to V N}}{dT} \times \frac{d\sigma^{N N \to N N}}{dT_{N N}}$$

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J. Stone et al., Nucl. Phys. **B143**, 1 (1978)

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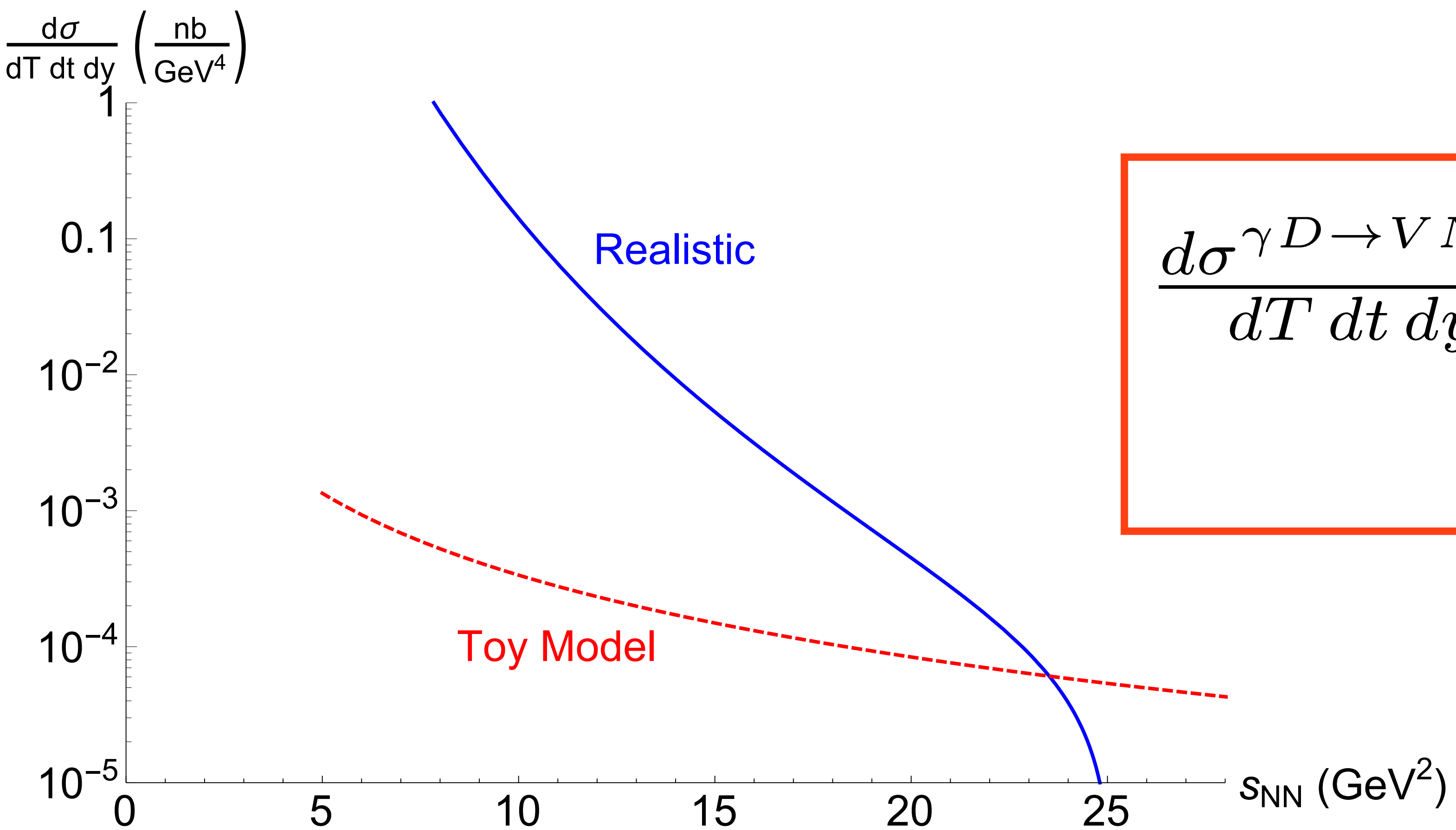

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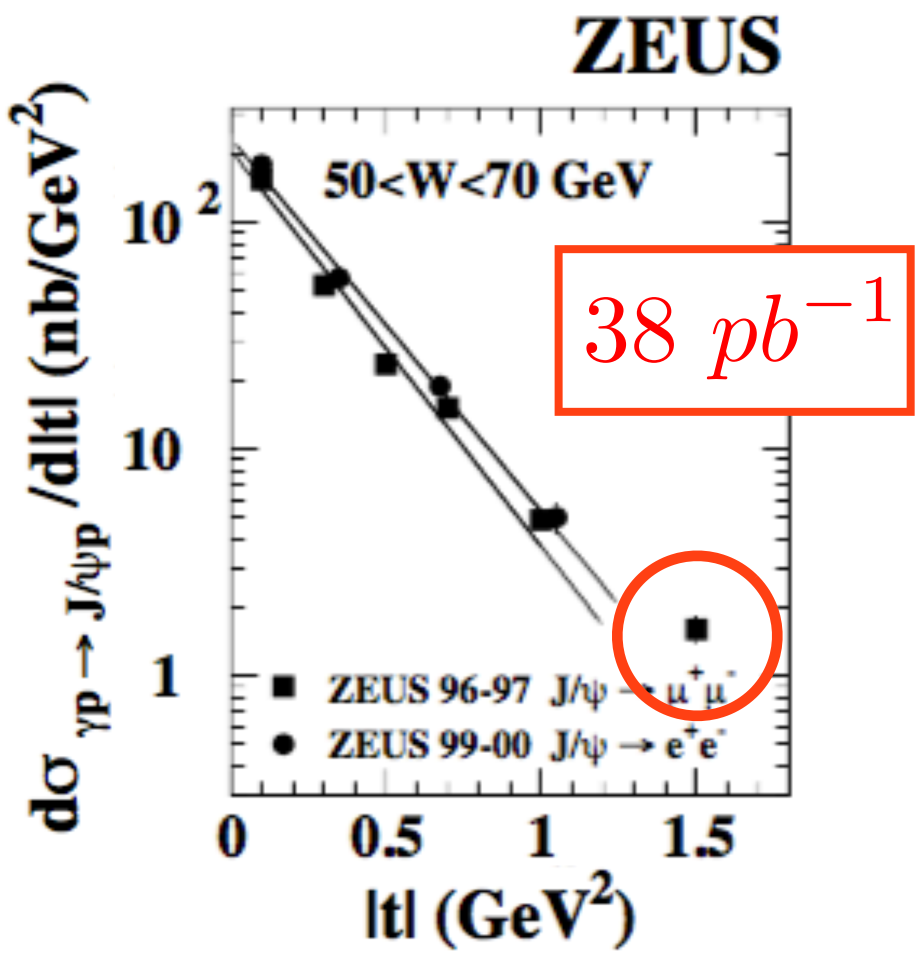
- NN rescattering: larger magnitude, but steeper falloff

Is It Measurable at an EIC?

- What luminosity would it take at an EIC to measure this process with the same statistics as at ZEUS?



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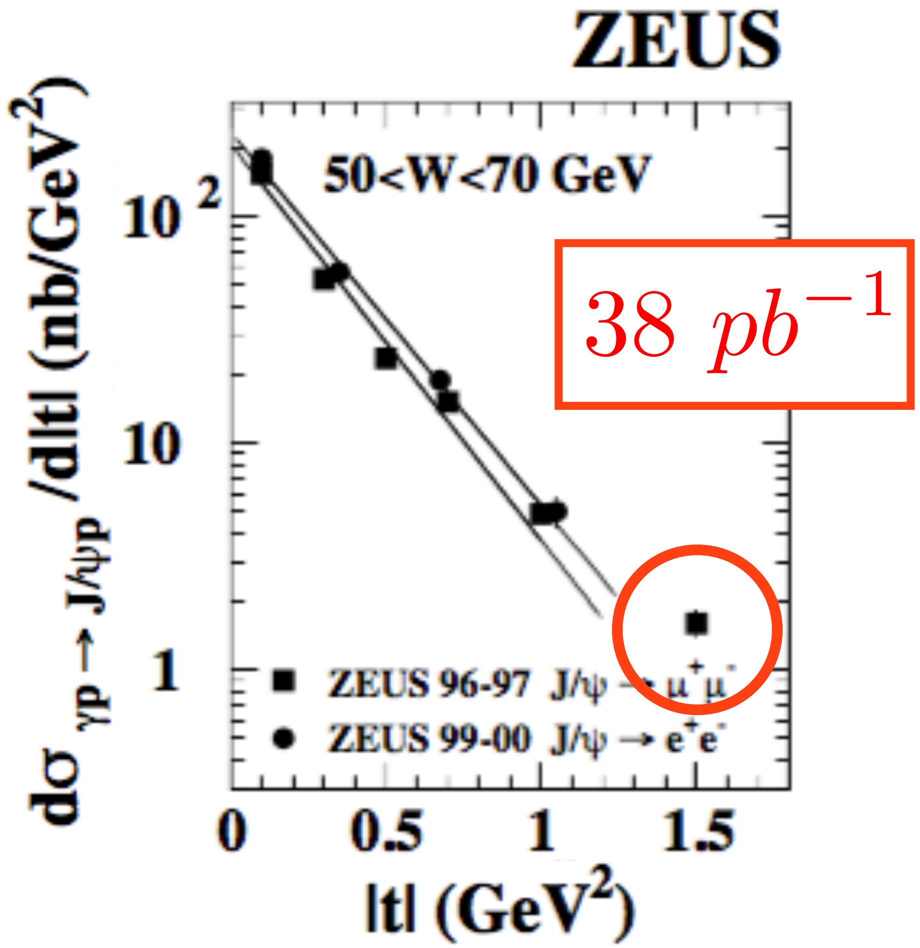
$$\mathcal{N} = \mathcal{L}_{ZEUS} \frac{d\sigma^{ZEUS}}{dT} \Delta T_{bin} = \mathcal{L}_{EIC} \frac{d\sigma^{EIC}}{dT\, dy} \Delta T_{bin} \Delta y_{bin}$$



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- EIC luminosity: $\mathcal{L}_{EIC}^{peak} \sim 10^{33} - 10^{34}\ cm^{-2} s^{-1}$

  $\mathcal{L}_{EIC}^{avg} \sim 1.6 \times 10^{32}\ cm^{-2} s^{-1}$

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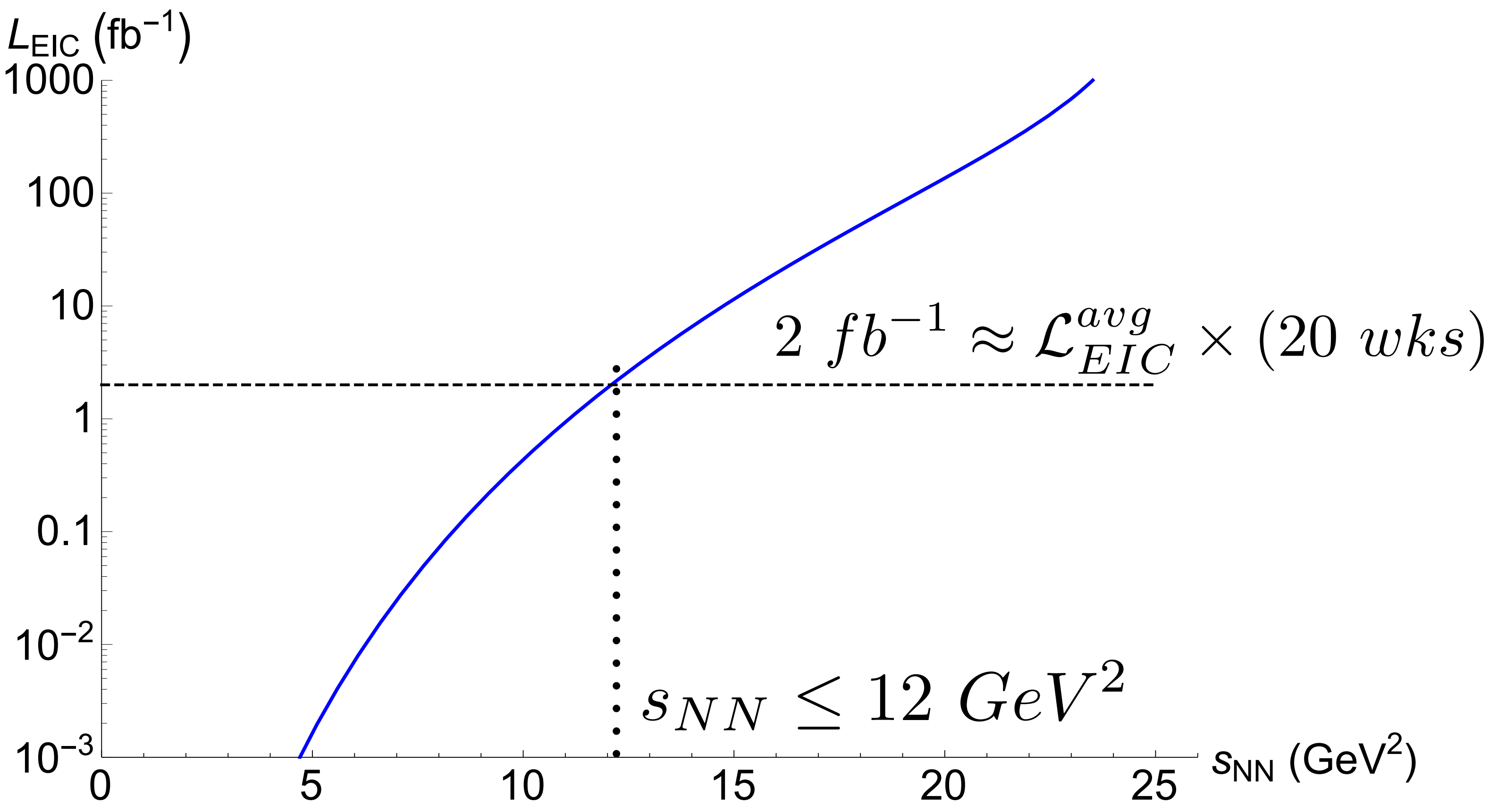

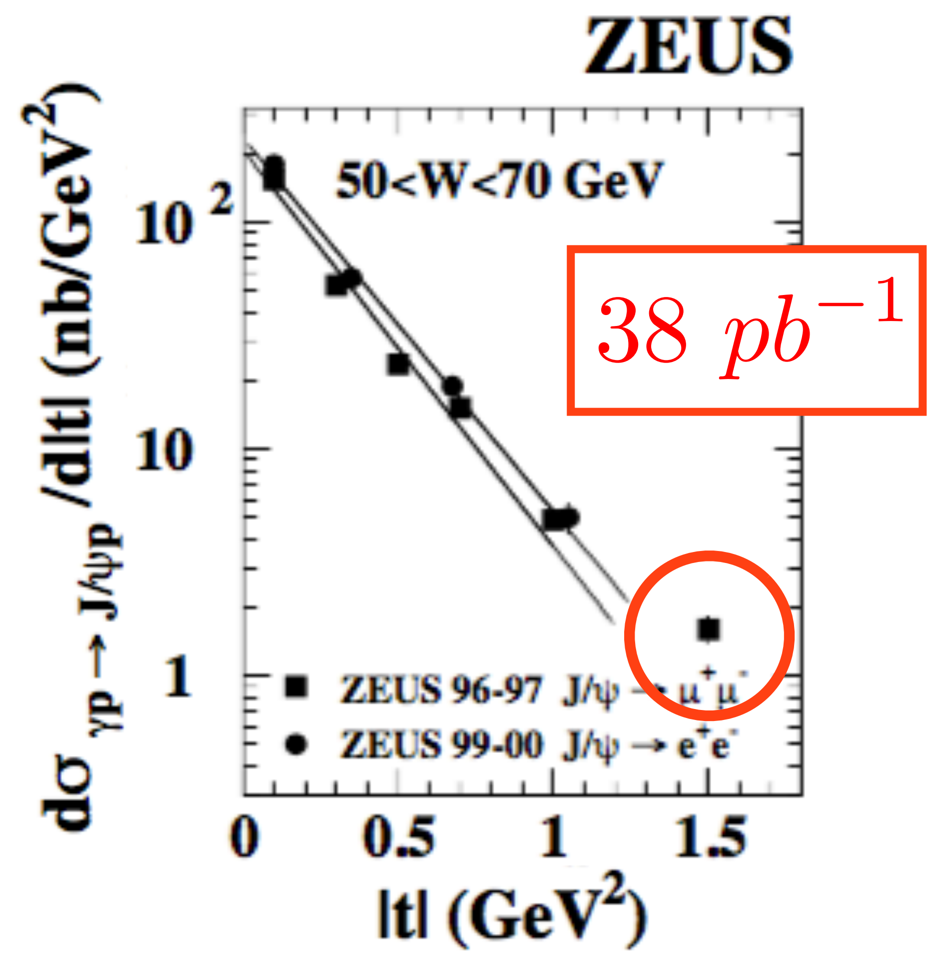

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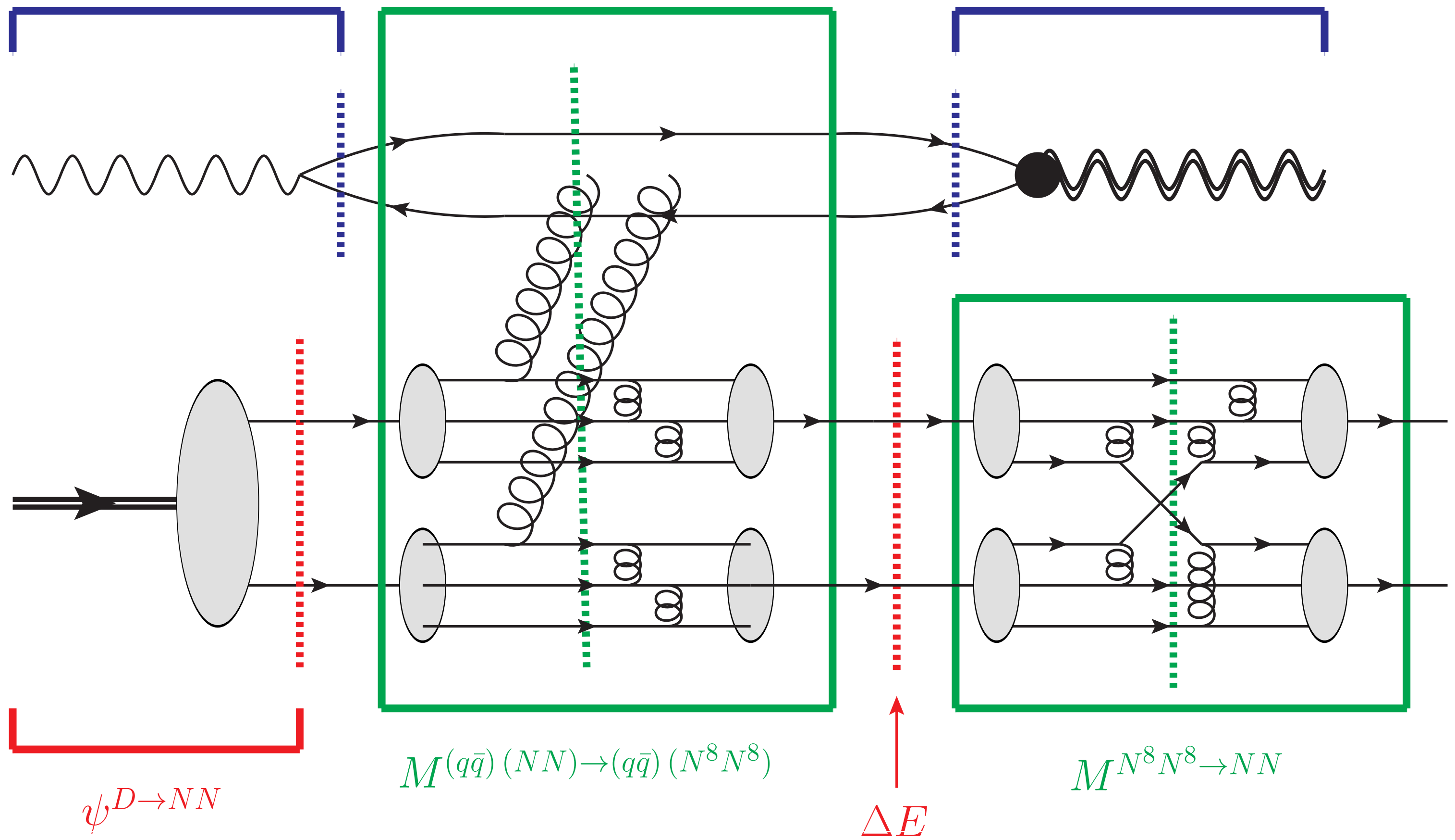
A Unique Opportunity: Color-Octet Scattering



- "Conventional" NN scattering is not the only accessible channel

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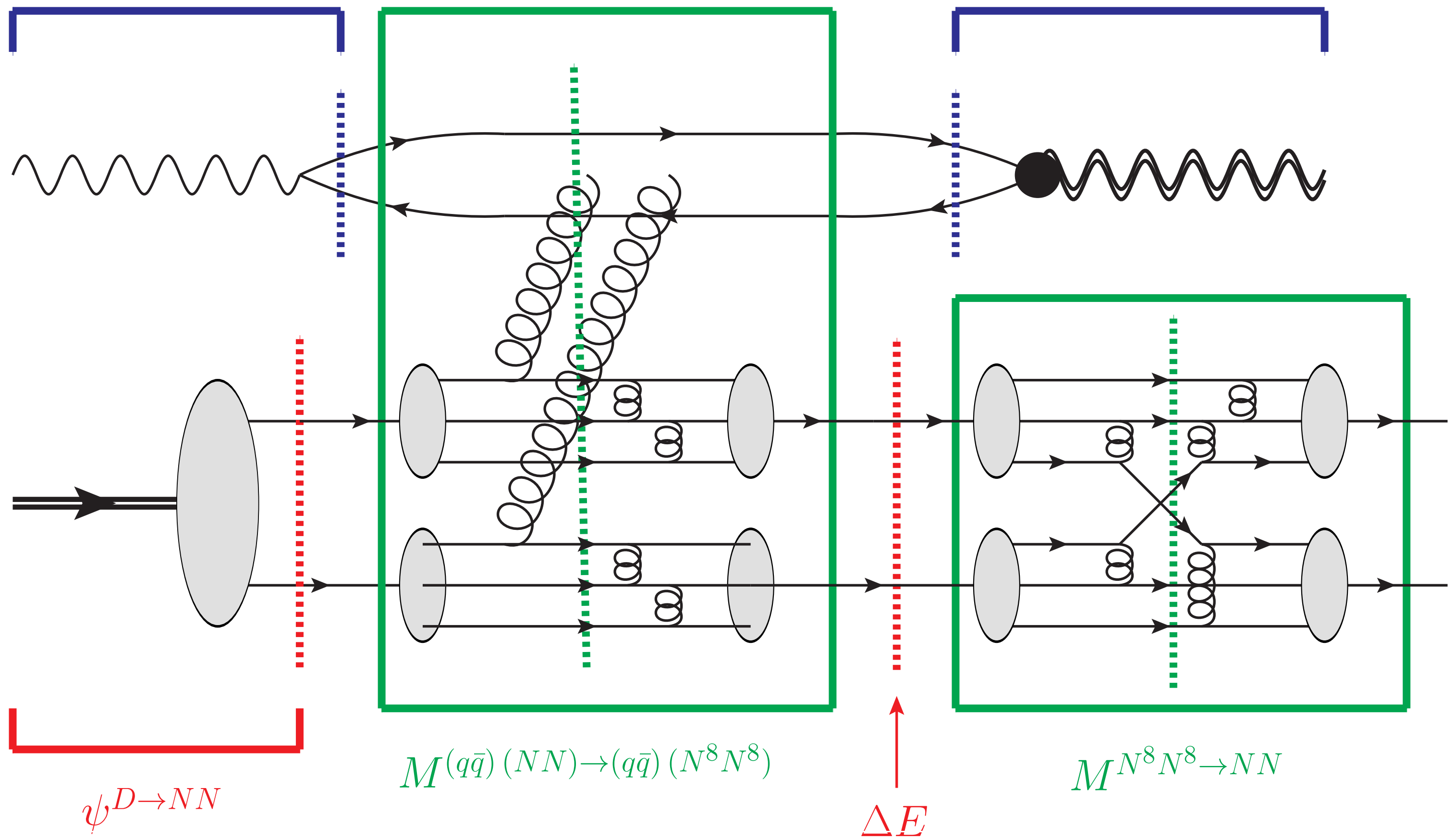

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➡ Like with the quark target, color octet rescattering can couple to the diffractive gluon exchange.

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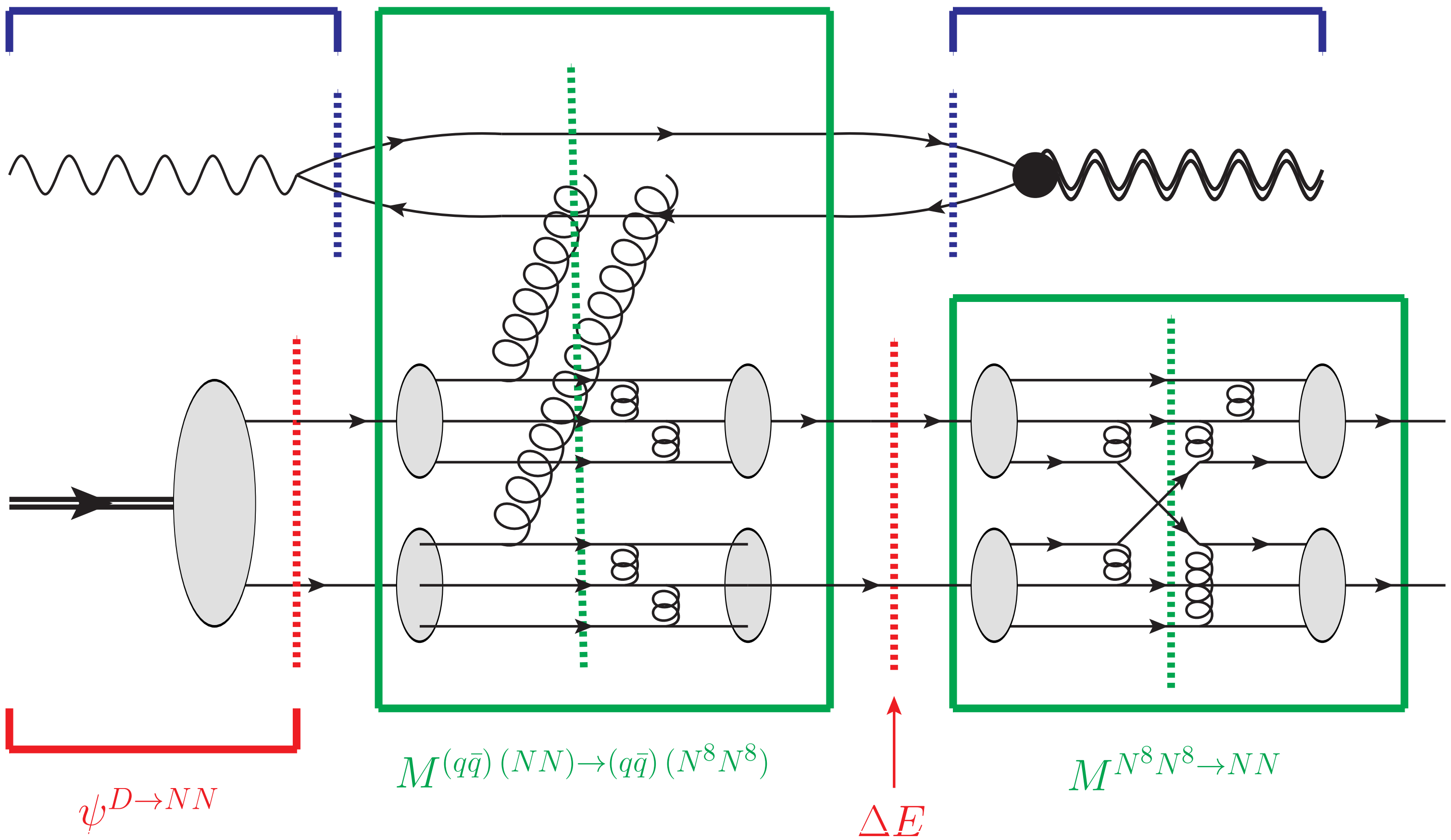

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➡ Like with the quark target, color octet rescattering can couple to the diffractive gluon exchange.

➡ Information about the octet / singlet "hidden color potential"

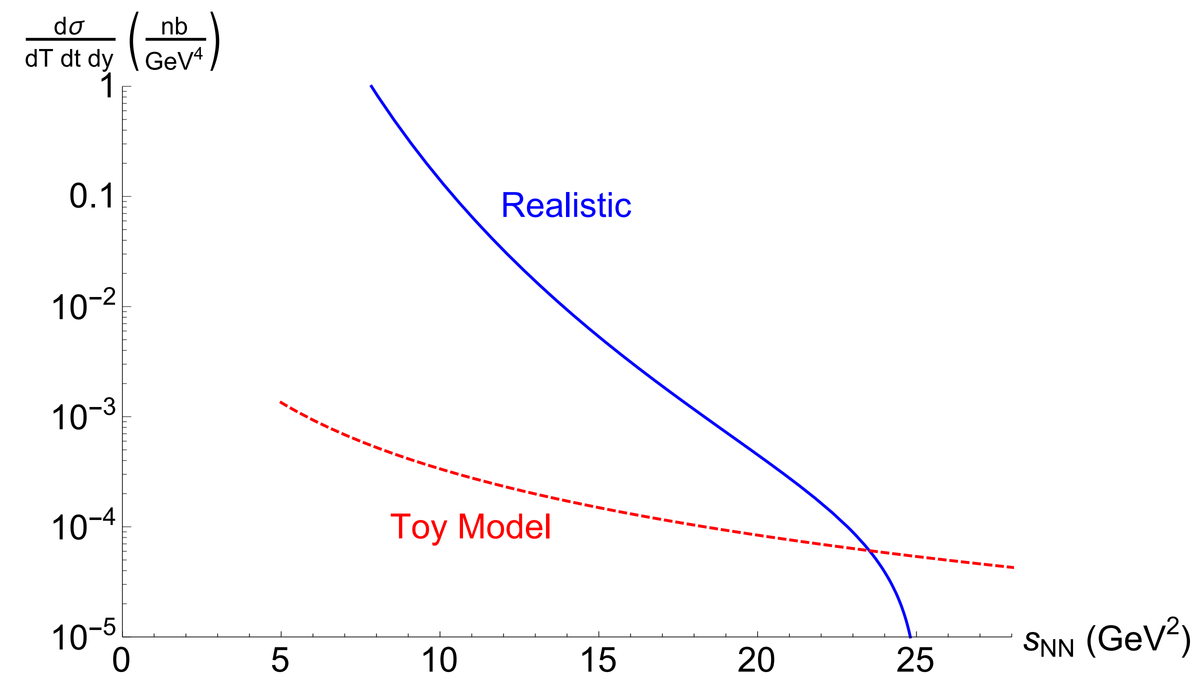
➡ Even conventional mechanisms (ie, Landshoff) have nonzero projection onto color octet quantum numbers.

V. Conclusions:

Looking Forward,
Looking Back

Outlook and Future Directions

- Quark target model and conventional NN scattering data provide useful upper / lower bounds for rates at an EIC.



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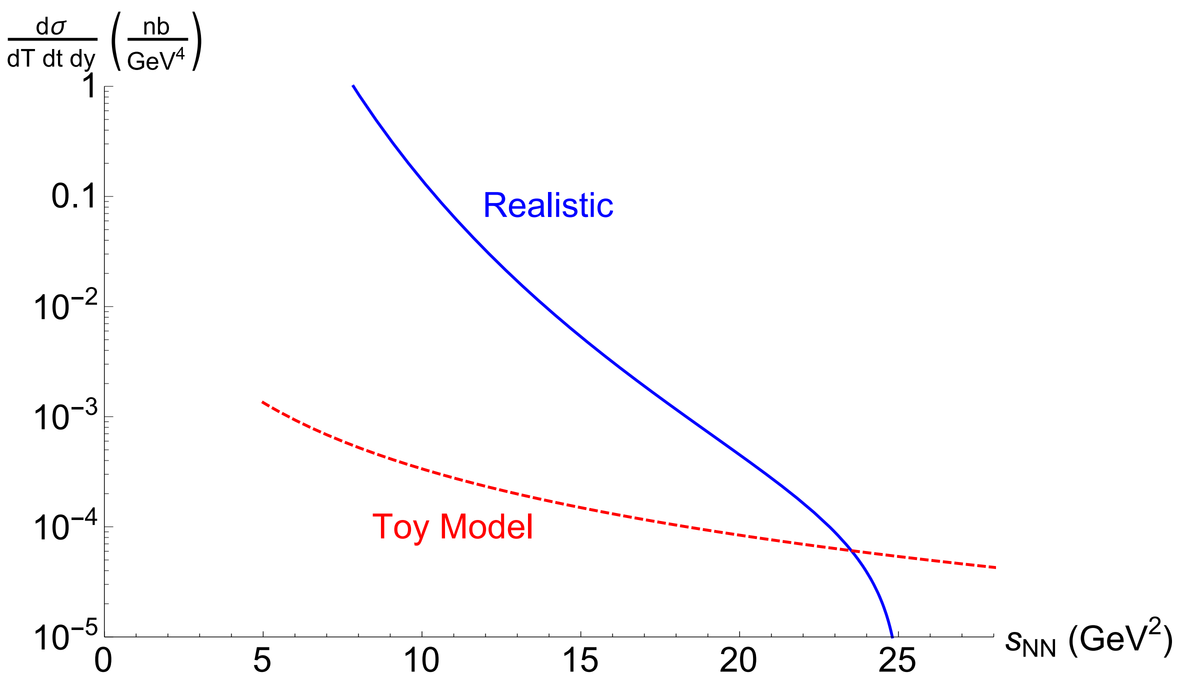

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➡ Other signatures? Spin asymmetries and azimuthal modulations?

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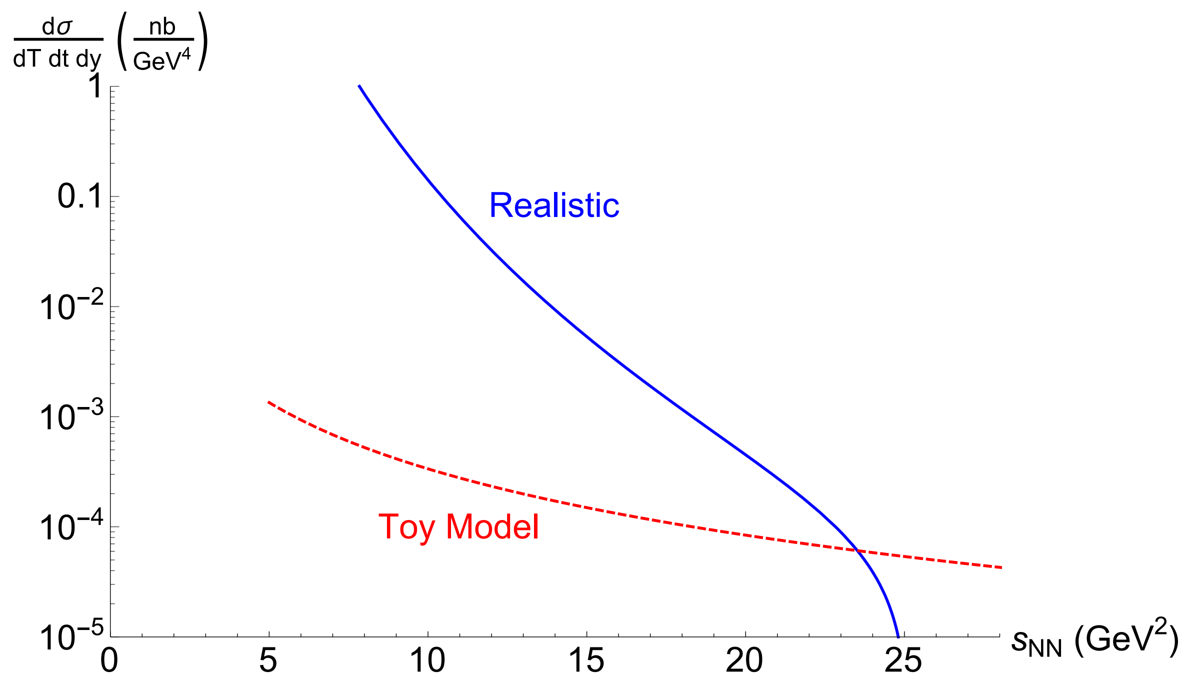

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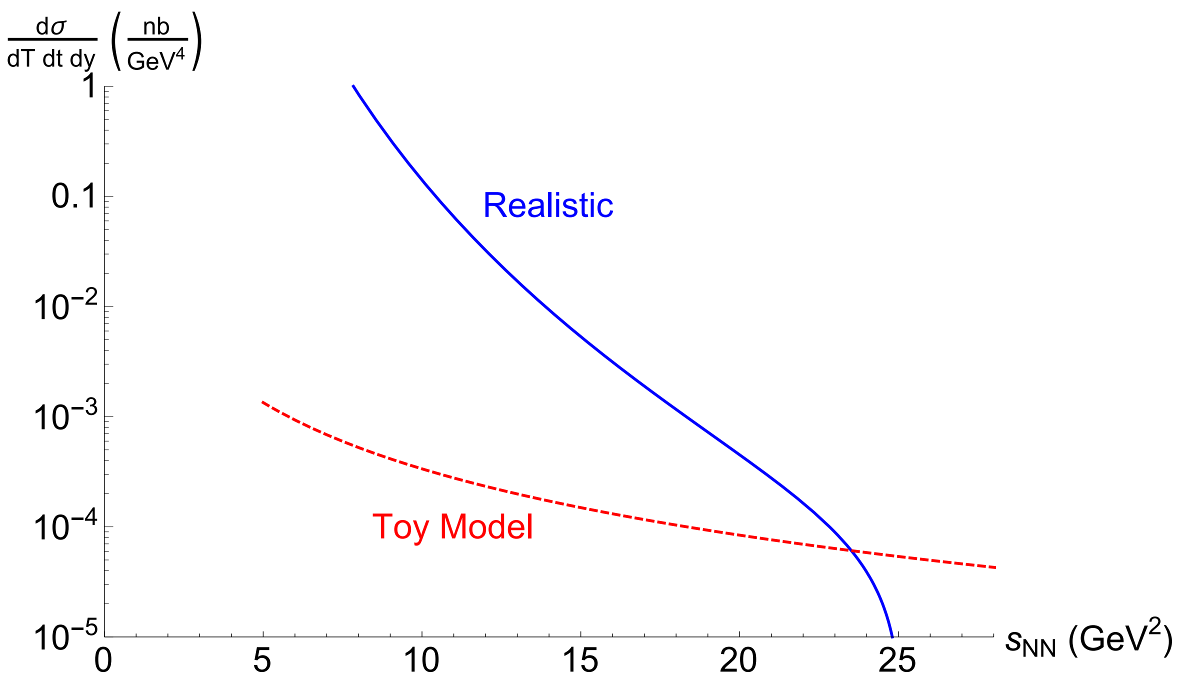

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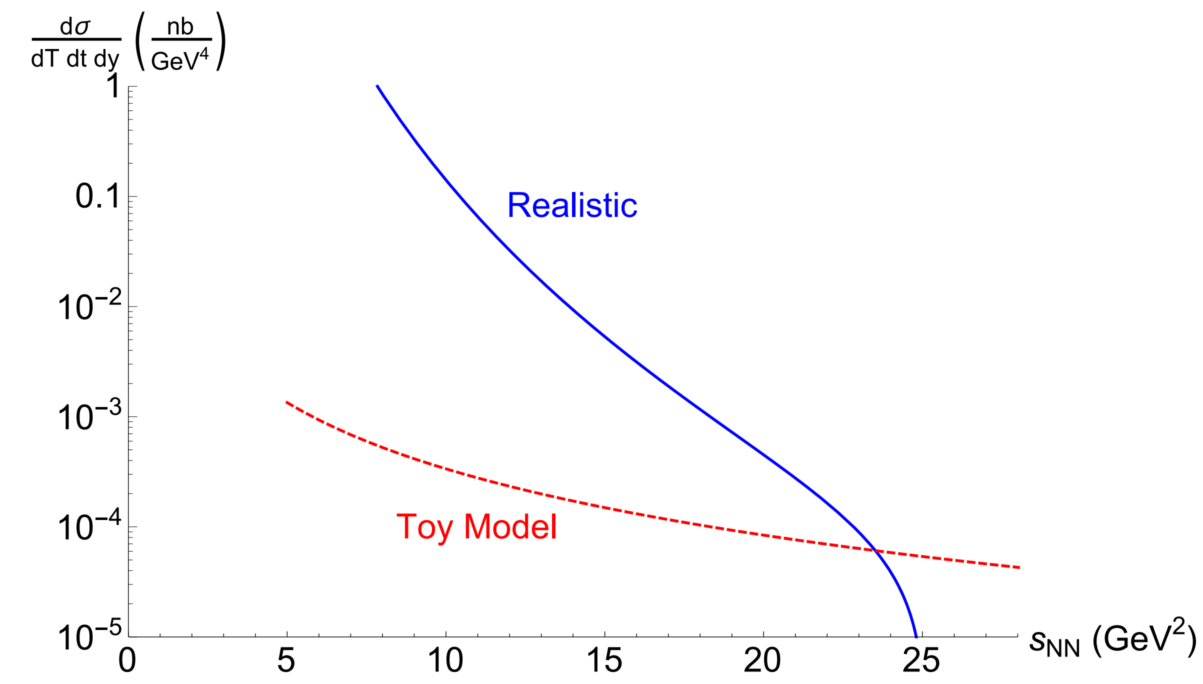

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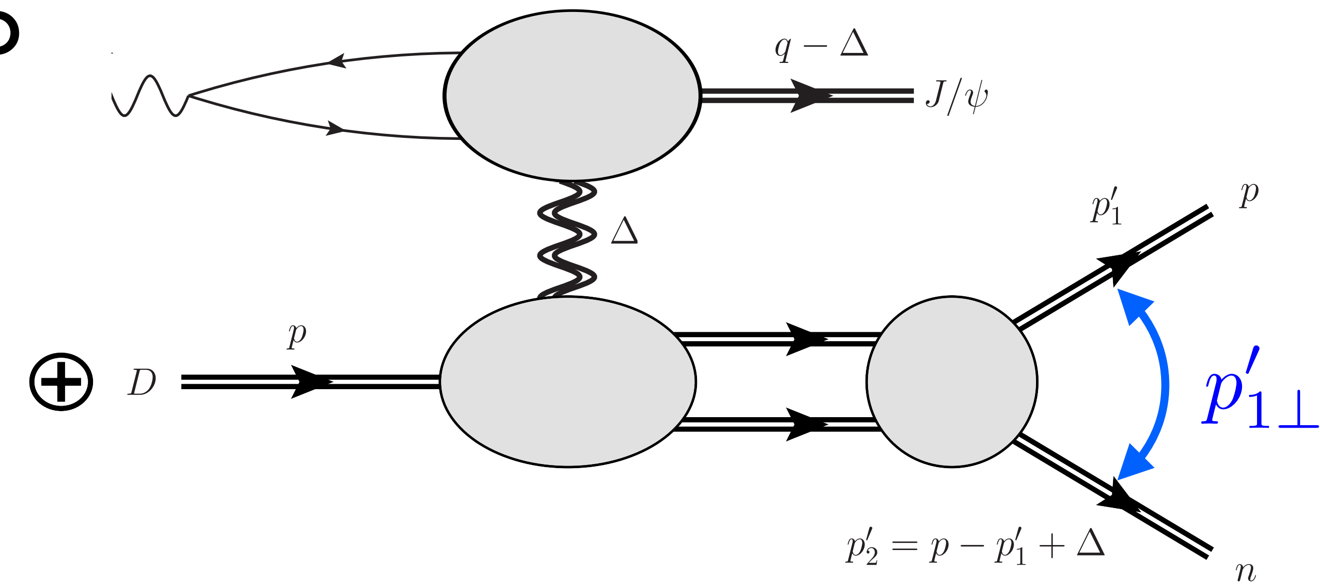
- Saturation corrections: multiple scattering at small x

➡ Could it drive up the cross-section?

- New reaction which is sensitive to short-distance NN scattering:

Hard exclusive meson production with hard deuteron breakup

$$e + D \to e + J/\psi + p + n$$



Summary

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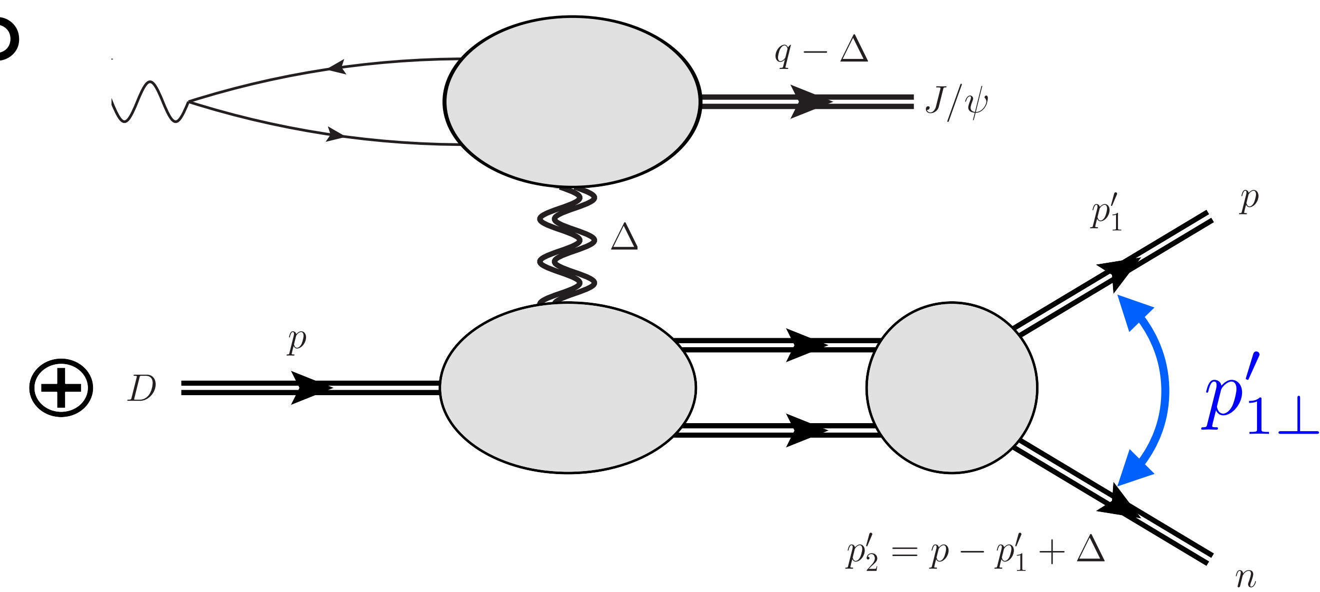
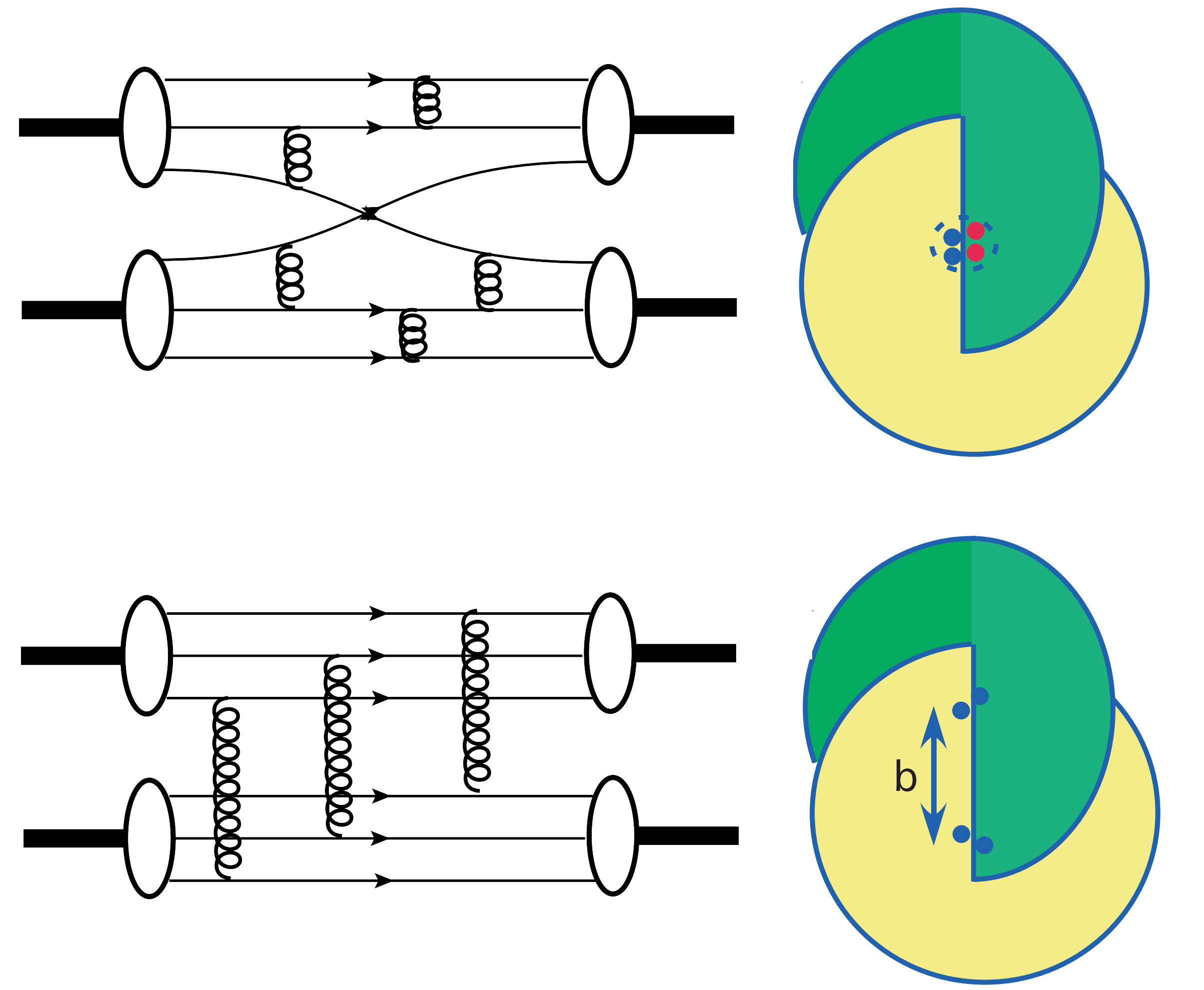


- Estimates show this process is measurable at an EIC, with a window in NN energies that can discriminate between scattering mechanisms.



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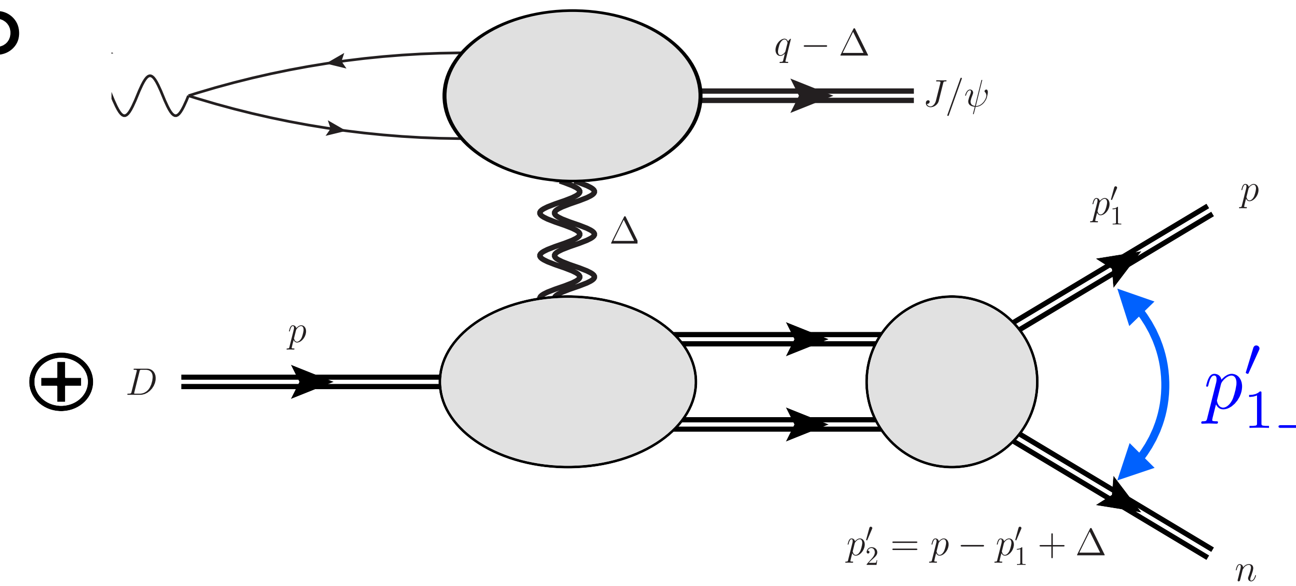

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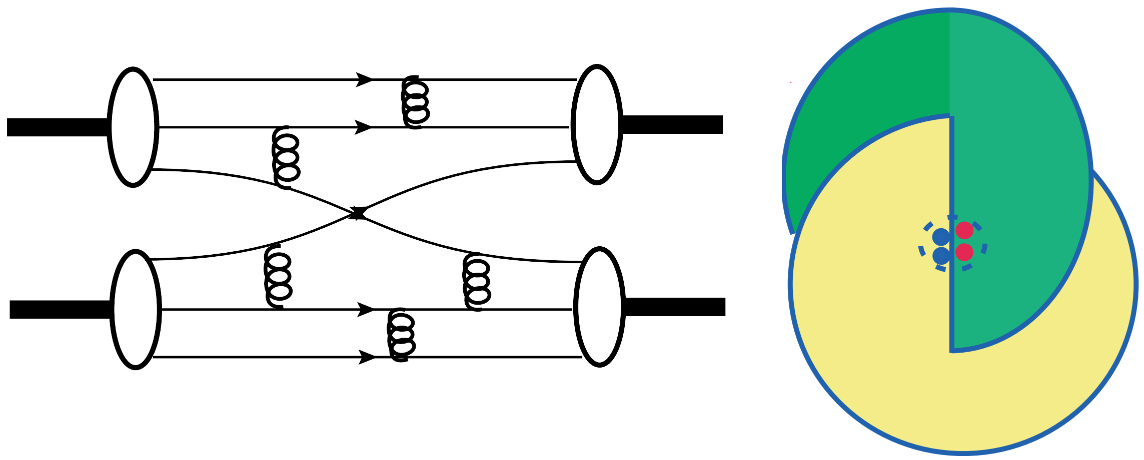

- This process is also sensitive to exotic "hidden color" scattering channels.